Development of Predictability and Condition Assessability Indices for PCCP Water Mains

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ABSTRACT

The condition of water and wastewater pipelines has been deteriorating with time and since this infrastructure is out-of-sight, the assessment has been neglected over the years. The advancement of technology in various fields has provided pathway for development of several technologies for assessment of the condition of pipeline systems. However, there is no standard guidance or tool for the utilities to use these technologies appropriately. The utilities are unaware of the present state-of- the- art technologies. The predictability and condition assessability indices will help utilities predict a probable failure and take steps to prevent it.

The predictability index will indicate the inherent, theoretical predictability of key types of pipe failures. The pipe failure predictability index would be a score calculated by identifying high priority pipe types, characterizing their failure modes, mechanism, conditions, and indicators, reliability of indicators, lead-time of the indicators, and other factors. The condition assessability index will indicate the technical and economical methods of preventing key types of pipe failures. The pipe failure condition assessability index is similar to the predictability index, but it takes into account the capability of existing inspection technologies for measuring the required failure indicator parameters.

Prestressed Concrete Cylinder Pipes are used in large diameter water pipelines throughout the United States to convey large volumes of water. Prestressed Concrete Cylinder Pipes are complex composite pipes. Therefore, prediction and prevention of failure of these pipelines is complex and requires a better understanding of the system. This research concentrates around development of Predictability and Condition Assessability Indices for PCCP pipelines.

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CHAPTER 1. INTRODUCTION

> *"New solutions are needed to what amounts to nearly a trillion dollars in critical water and wastewater investments over the next two decades. Not meeting the investment needs of the next 20 years risks reversing the public health, environmental, and economic gains of the last three decades."* (Water Infrastructure Network (WIN), 2000).

Most cities and towns started building drinking water and collection systems over 100 years ago and many of these systems have not received adequate upgrades, maintenance, repair, and rehabilitation over time (USEPA, 2005). Today, municipal governments are facing an infrastructure crisis requiring costly renewal beyond their capacity. There has been a steady decline in the state of our water infrastructure over the past two decades and a growing concern is that these facilities may be inadequate both for current requirements and projected future growth (USEPA, 2005). Funding for these needs is limited, and a deferred maintenance, out-of-sight, out-of-mind philosophy still prevails in many regions. Recently, for example, the American Society of Civil Engineering (ASCE) in its 2005 assessment of the nation's infrastructure assigned the grade "D" and estimated the five-year investment needs to be in excess of $1.3 trillion (ASCE, 2005). It is estimated that the cost of replacing all water mains in the United States would run to $348 billion (ASCE, 2000). With billions of dollars being spent yearly for water infrastructure, the systems face a shortfall of at least $21 billion annually to replace aging facilities and comply with existing and future federal regulations (Water Infrastructure Network (WIN), 2000). Monetary investment alone will not resolve this dilemma; it must be met with a new approach to sustainable water infrastructure engineering and management. There is a critical disconnect between the methodological remedies for infrastructure renewal problems and the current sequential or isolated manner of renewal analysis and execution. This disconnect manifests in the need for a holistic systems perspective. New tools are needed to provide the intellectual support for decisions necessary to sustain economic growth, environmental quality, and improved societal health.

Measure of Condition Assessment: Condition Index, Prediction Curve, and Proposed Predictability and Condition Assessability Indices

Infrastructure Management is an administrative process of creating, planning, and maintaining our infrastructure. It is an integrated, inter-disciplinary process that ensures infrastructure performance over its lifecycle. Where, lifecycle is entire time from design through decommissioning.

Figure 1 illustrates the Infrastructure Asset Management Framework. This describes the various stages of the infrastructure asset management.

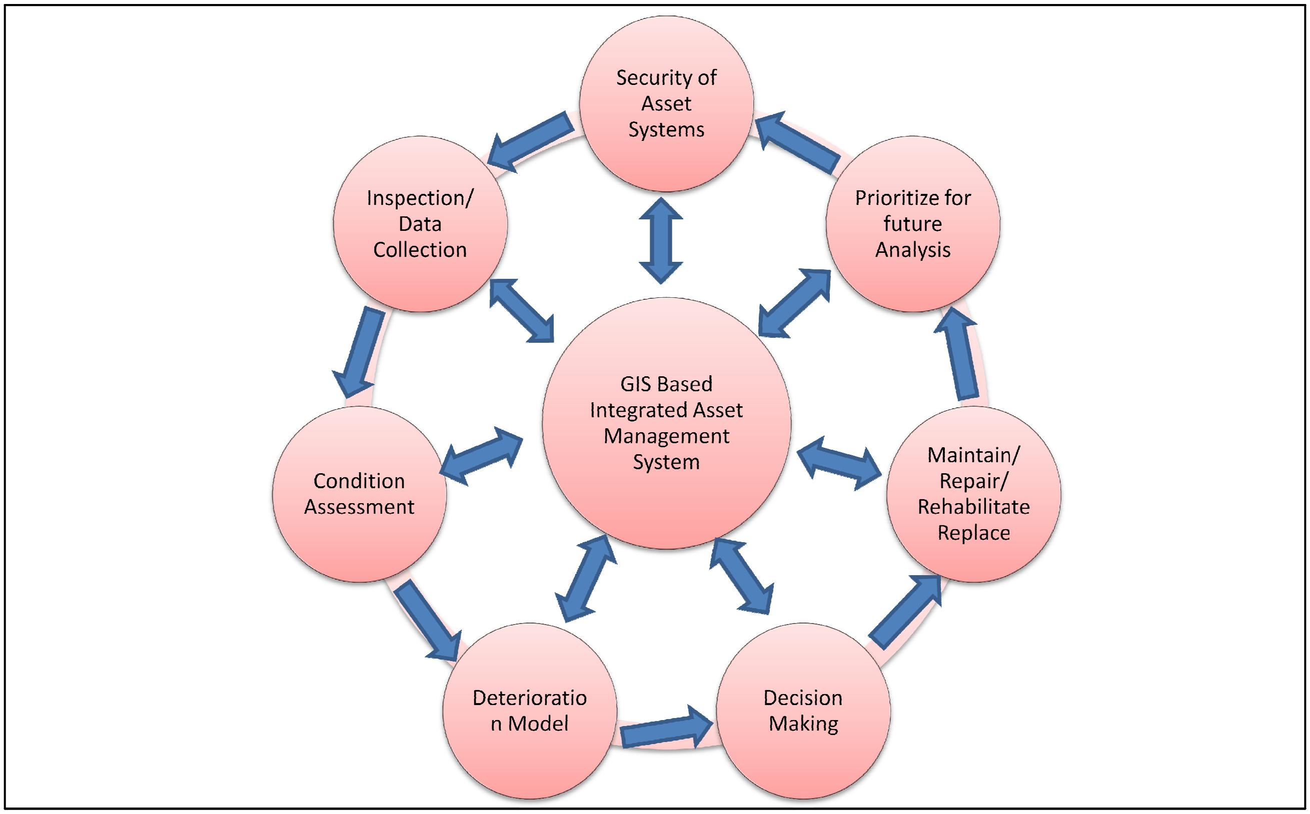

Figure 1: Infrastructure Asset Management Framework

Evaluation of the existing infrastructure is an important phase of the infrastructure asset management. Inspection/ Data Collection and Condition assessment form the base for development of deterioration models.

The existing evaluation tools for the pipe system are condition index and prediction model. The proposed evaluation tools are predictability index and condition assessability index. Predictability is a concept new to the water pipeline infrastructure. However, this concept had been used earlier in various other fields like climate prediction model, water quality prediction, etc.

Condition Index:

Condition Index is a numerical index, which is used to indicate the existing condition of the pipeline system. The Condition Index being developed takes into consideration the system as a whole instead of taking into account only the pipe and its structural condition. Below is an example of a condition index in Figure 2. Depending on available data the division of the index may vary.

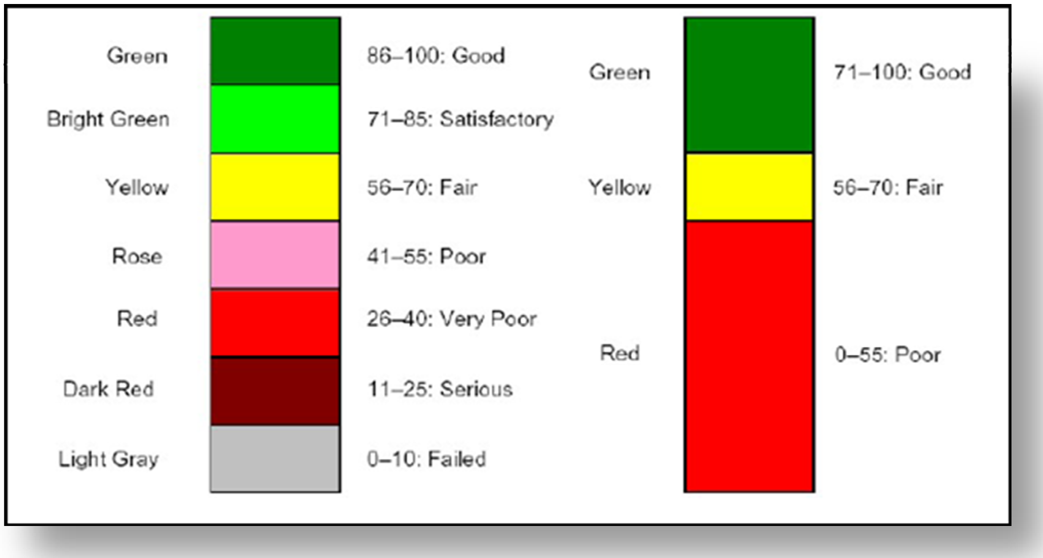

Figure 2: Example of Condition Index

An example of a condition index is the Pavement Condition Index (PCI). The PCIs range from zero to 100, with 100 corresponding to a newly constructed pavement. The provision of a range of 100 points allows enough breadth for more accurate rating and ranking of pavement sections (Chan et al, 2006). Commonly, the 0 to 100 scale indicates the following conditions as shown in Table 1:

Table 1:Range of Pavement Condition Index

100-90	Excellent Pavement Condition
89-80	Good Pavement Condition
79-70	Fair Pavement Condition
69-60	Poor Pavement Condition
<60	Critical Pavement Condition

Prediction Model:

Prediction Model is the time varying condition of a given pipe. In this model, the pipe condition is considered to be excellent at the time of installation assuming no imperfections during manufacturing and installation. As time progresses the condition of the pipe deteriorates. Pipe renewal improves the condition of the pipe, thereby increasing the life of the pipe. An example of the prediction model is shown below in Figure 3.

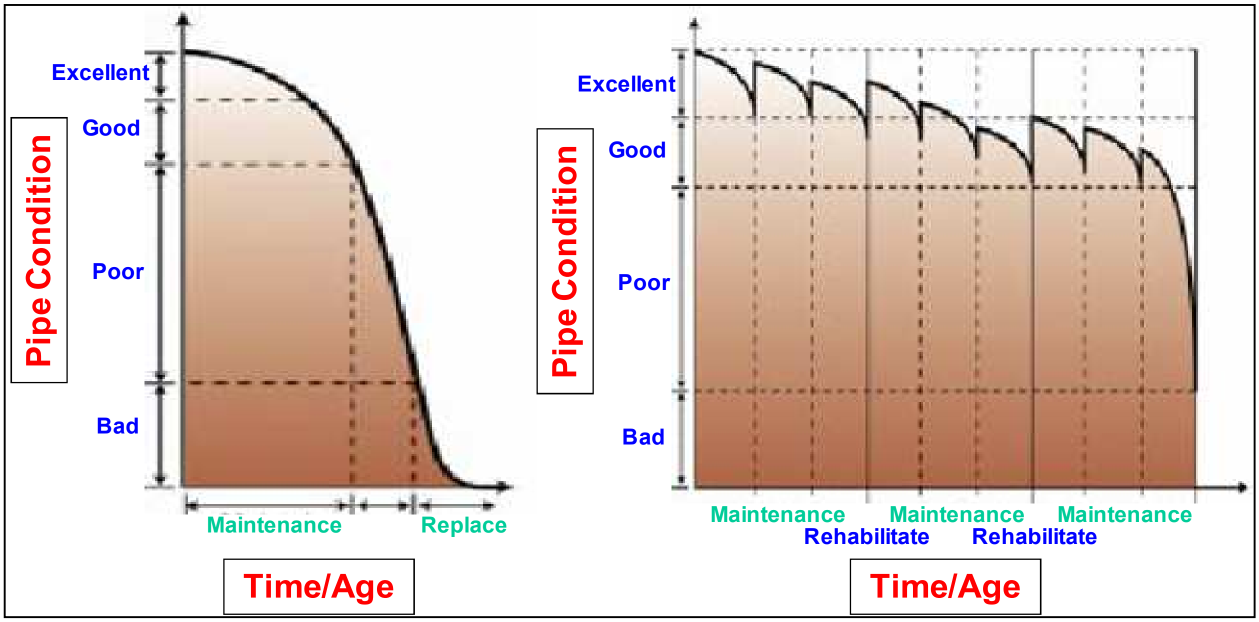

Figure 3: An Example of a prediction model

Predictability Index and Condition Assessability Index:

According to AWWA, there is substantial interest and research activity regarding improvement of structural condition assessment technologies for water mains. However, tracking progress is difficult because there is a wide array of activities in different organizations and locations and many factors to consider. In addition, perhaps most importantly, there is no standard set of factors and conditions established to measure and report performance. The goal of this research is to explore the feasibility and value of developing procedures for calculating predictability and condition assessability indices for selected high-risk pipe situations.

The predictability index will indicate the inherent, theoretical predictability of selected key types of structural failure. The pipe failure predictability index would be a score calculated by: (a) identifying high priority pipe types, (b) characterizing their failure modes, mechanisms, conditions, and indicators, (c) defining specific, representative pipe failure scenarios of interest, (d) determining whether there are reliable indicators of the onset of failure, and when they occur with respect to failure, and (e) developing a predictability score for the selected, representative pipe situations based, for example, on the number, reliability, and lead-time of the indicators. If a failure type is inherently unpredictable (i.e., there is no apparent warning before failure occurs) it is fruitless to seek to develop condition assessment technologies for this type of situation, and it should have a low predictability index. On the other hand, if reliable indicators of failure are discovered, then this will increase the predictability of failure, and the predictability index.

The condition assessability index will indicate the technical and economic feasibility of preventing selected key types of structural failure. The pipe failure condition assessability index is similar to the predictability index, but it also takes into account the capability of existing (or proposed) inspection technologies for measuring the required failure indicator parameters at the quantity, quality, and timeliness levels required to prevent failures. Cost is a factor for further refinement.

Pipe scenarios that have a high predictability index and a low condition assessability index are candidates for condition assessment technology development or technology transfer. The indices will provide common yardsticks for measuring and communicating the state-of-the-art regarding theoretical and actual condition assessability of the most important classes of pipe structural failure. These indices will quickly indicate to the user, regulatory, and research communities the relative level of difficulty involved in predicting and preventing key types of failures. Recalculating the indices over time will give a clear indication of progress (or lack of it) regarding the understanding of pipe failure mechanisms, critical conditions, and indicators, and regarding the ability to measure and analyze critical conditions and indicators(EPA,2007).

Relationship between Predictability Index, Condition Index and Prediction Model

The Relationship between the Predictability Index, Condition Index and Prediction Model is explained in Figure 4. Predictability Index forms the guidelines towards the future condition assessment programs and is primarily a theoretical index which understands all the possible failure modes and mechanism along with the mechanisms that cause it. Condition Index, however, is a numerical measure for the existing condition of the pipeline. This takes into account the inputs from the condition assessment procedures followed on the pipeline. Prediction Model, on the other hand, is an estimate of the lifetime performance of the pipeline depending on its present condition and lead-time of the factors contributing towards the pipe system performance.

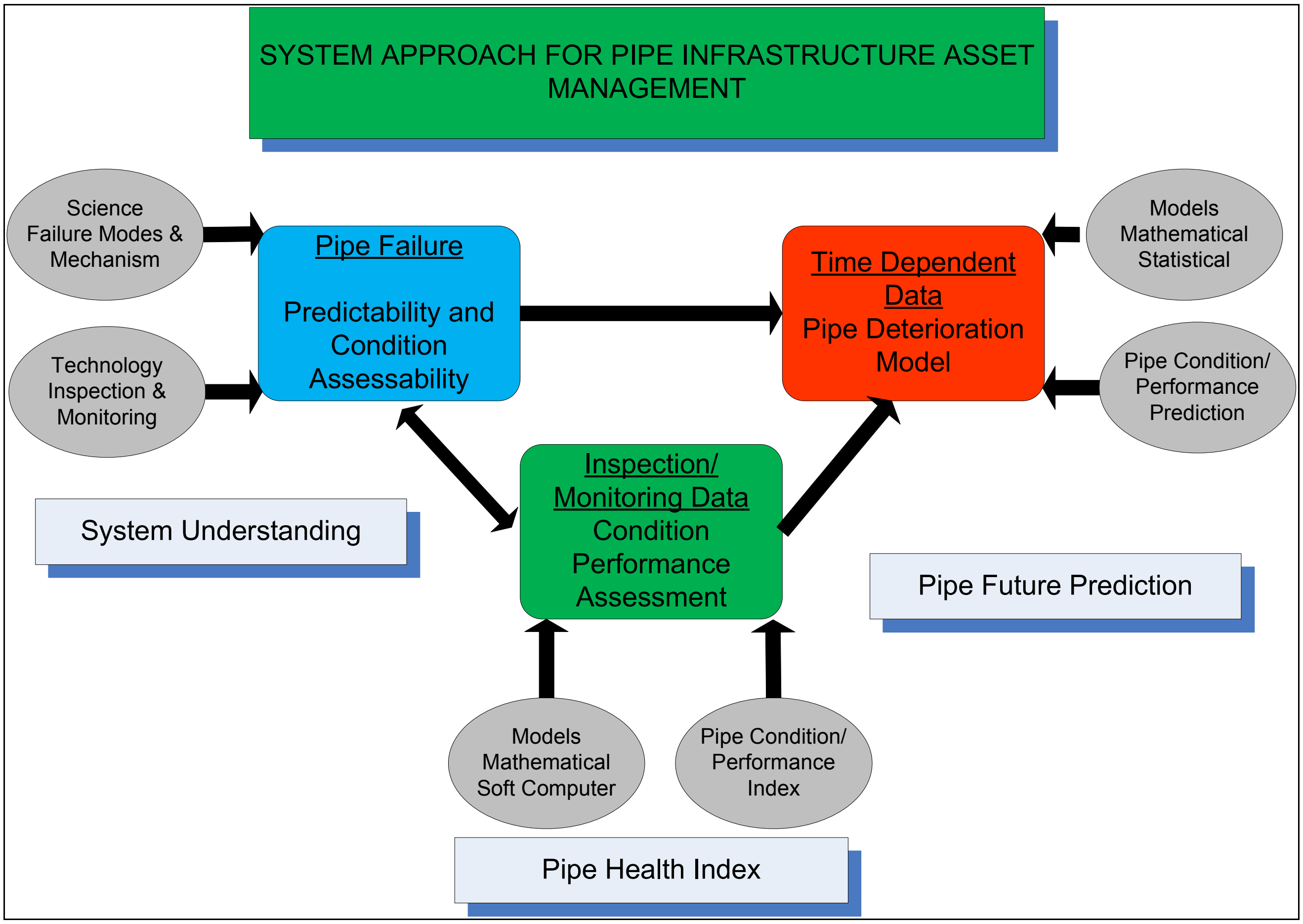

Figure 4: Relationship between Predictability Index, Condition Index and Prediction Model

Objectives of the Research

The major research objectives are:

1. Development of a procedure for calculating predictability and condition assessability index
2. Methodology to calculate the predictability index for high-risk pipe situations
3. Methodology to calculate the condition assessability index for high-risk pipe situations
4. Calculate the predictability index for two selected, high-risk pipe situations
5. Calculate the condition assessability index for the same scenarios for two common and two innovative condition assessment approaches

This research aims at meeting the requirements stated in task 2.5 in the Performance Work Statement according to which predictability and Condition Assessability indices should be derived for selected high-risk pipe situations. This is in order to establish a way to measure and report performance of various condition assessment technologies being developed in the recent times and beyond.

Approach for the Objective

This research summarizes the development of Predictability Index and Condition Assessability Index for water mains. It contains an extensive literature review of state-of-the-technology and various failure modes and mechanisms of all pipes as a part of this procedure. Overall, this research contains the complete background, procedure and methodology to calculate the Predictability Index and Condition Assessability Index.

CHAPTER 2. LITERATURE REVIEW

One of the most significant challenges faced by the infrastructure is aging. As many civil engineering projects begin to approach their design lives and the option for new construction fades in light of decreasing capital-expenditure budgets, it will be necessary to exercise repair, evaluation, maintenance and rehabilitation (REMR) strategies that can extend the design life and serviceability of those facilities (Anderson et al, 1995).

From literature and available references, in the case of Water pipeline infrastructure, there exists no standard tools for the utilities to evaluate their infrastructure and maintain appropriately. The Predictability and Condition Assessability Indices aim at helping the utilities evaluate their system and guide them towards the appropriate measures. The study required for the development of the Predictability index is the understanding of the pipe system and the calculation methodology. The study required for the development of the Condition Assessability Index is the understanding of the various condition assessment technologies (both existing and emerging) and the economic evaluation for the selection of technologies.

Understanding the High-Risk Pipe Failure Situation, Consequences, and Occurrences

Case studies suggest that the evaluation of pipe failure for the development of the predictability index requires further study on the failures. The occurrence of the failure and the severity of its consequence indicate the necessity of any inspection or evaluation. The most common factors that affect the failure of the pipe are shown in Table 2. These factors were listed in the US EPA white paper [Royer, 2005] on improvement of structural integrity monitoring for drinking water mains. The potential preventable types of water main breaks listed in the US EPA white paper are listed in Table 3.

Table 2: Example of Common Factors for Water Main Breaks

Main Break Occurrence Factors	
Chemical Stressors	Internal & external corrosion caused by factors such as aggressive water or soil, microbes, stray currents, oxygen gradients, & bimetallic connections
Physical Stressors	Damage during transport, unloading, storage, & installation Traffic loads Soil loads from differential settling caused by bedding washout from water leakage, drought, expansive clays, & landslides Point loads from projecting rocks, etc. Internal, radial loads from water pressure fluctuations Axial loads from seismic activity, soil movement, & water hammer Thermal stress from temperature differences between water, pipe, & soil; freezing/expansion of water; & soil frost loads Damage by excavating equipment that causes or accelerates failure Damage to external coatings or internal linings that enables accelerated corrosion
Other Factors	Aging (i.e., the accumulation of effects over time from external chemical & physical stressors & from equilibrium reactions within the pipe (e.g., brittleness)) Pipe flaws arising from design, raw materials, manufacturing, or installation errors

Table 3: Example of Potentially Preventable Types of Water Main Breaks

Examples of Potentially Preventable Types of Main Breaks
Cold weather main breaks whose occurrence in typical winter conditions can be accurately forecast in the previous summer based on physical condition data
Main breaks that are preceded by:
Leaks that cause gradual bedding erosion and detectable excess strain Gradual soil movement and excess strain Increasing leak rate Gradual wall thinning Pitting Gradual wall deformation Mis-alignment Acoustic emissions from wire breaks, cracks, and leaks Coating failure that changes pipe electrical properties Cathodic protection partial or total failure

The probability of occurrence of these failure modes needs to be evaluated for future analysis. The high-risk situations for pipelines are the situations of the pipe existence, which have higher probability of failing.

High risk scenarios are described as situations that have a high probability of failure (risk= consequence*liability). Table 4 and Table 5 list the examples of such high consequence breaks and the type of adverse effects the pipe breaks have as listed in US EPA white paper on improvement of structural integrity monitoring for drinking water mains.

Table 4: Example of High Consequences Water Main Break Scenarios as stated in the US EPA white paper on improvement of structural integrity monitoring for drinking water mains.

Example High Consequence Main Break Scenarios		
Critical	Large population	Hospital
Customers	Fire protection	Limited alternative supply
	Key industry/defense/government site	
Critical	Industrial/commercial/residential	
Surroundings	Highway/bridge/tunnel/railroad/subway/airport Critical water main/sewer/communication	
	Energy pipeline/cable	
Difficult Response	Large main Difficult terrain Heavy traffic	Remote site River crossing Extreme temperatures

Table 5: Example of Types of Adverse Effects from Water Main Breaks

Types of Adverse Effects from Water Main Breaks		
Health and Environment	**Economic**	**Safety & Inconvenience**
Public Health Problems Waterborne disease outbreaks Low pressure • Presumptive boil water notices Noncompliance • Primary WQ standards Loss of drinking/bathing water Loss of water for sewage Sewer overflows from flooding	**DW Utility** Lost revenue Response costs System damages/repairs Claims Deferral of maintenance	**Public Safety** Fire fighting water loss Worker hazards Traffic accidents • Flooding • Icing • Disruption Electrical shock hazards
Other Water Quality Problems Noncompliance • Secondary WQ standards	**Non-DW Utility** Property damage • Residential • Commercial • Industrial Walk-in business losses Production losses Infrastructure Damages/outages • Electric/gas/steam • Sewer • Communication • Road/tunnel/bridge • Train/subway/airport	**Public Inconvenience** During main break During remediation
Resource Depletion • Water • Energy	Resource Depletion • Water • Energy	
Environmental Degradation • Chlorinated water discharged to sensitive areas	Environmental Degradation • Chlorinated water discharged to sensitive areas	

Calculation Methodology for Predictability Index

In order to evaluate the Predictability Index, the process also involves a calculation methodology. This calculation can be achieved by the following ways:

1. Arithmetic Calculations
2. Fuzzy Logic
3. Neural Networks

Arithmetic Calculations

We have done intensive literature study on various arithmetic calculation procedures being used for the calculation of similar index calculations. These arithmetic calculations are listed below. Most of these calculations have been used for the calculation of water quality [Swamee and Tyagi (2000)].

Weighted Arithmetic Mean Index

This was the most commonly used method for Index calculation. A known problem with such an index is eclipsing. That is, if one sub-index shows poor quality, but aggregated index does not reflect the overall poor quality. The arithmetic representation of such a calculation is reflected below.

$$I = \sum_{i=1}^{N} w_i s_i$$

Where
I= aggregate index
N= number of sub-indices
w_i= *i* th weight
s_i= *i* th sub-index
The weights w_i indicate the relative importance s_i

$$1 = \sum_{i=1}^{N} w_i$$

Weighted Geometric Mean

Weighted Geometric Mean also faces the same problem as the weighted arithmetic mean. With a smaller (non-zero) weight assigned to a low (but non-zero) sub-index, aggregation may be eclipsed. The arithmetic equations are shown below.

$$\mathrm{I} = \prod_{i=1}^{N} s_{\mathrm{i}}^{\mathrm{wi}}$$

Where
I= aggregate index
N= number of sub-indices
w_i= *i* th weight
s_i= *i* th sub index
The weights w_i indicate the relative importance s_i

$$1 = \sum_{i=1}^{N} w_{\mathrm{i}}$$

Square root of the harmonic means

This aggregation suffers ambiguity. This calculation was used for water quality calculation. It had results where the water quality was acceptable and the aggregation result shows unacceptable.

$$I = \left(\frac{1}{N}\sum_{i=1}^{N} s_{\mathrm{i}}^{-2}\right)^{-0.5}$$

Where
I= aggregate index
N= number of sub-indices
w_i= *i* th weight
s_i= *i* th sub-index

Minimum operator or Maximum operator of the sub indices will be the aggregation

This has been used in the case of water quality. Though this does not suffer eclipsing, it fails to give the composite picture of the water quality.

$$I = \text{Min or Max } (s_1, s_2, s_3, \ldots s_n)$$

Fuzzy Logic and Neural Network

Fuzzy logic is a form of multi-logic derived from fuzzy set theory to deal with reasoning that is approximate rather than precise. In contrast with binary sets having binary logic, also known as crisp logic, the fuzzy logic variables may have a membership value of not only 0 or 1. Just as in fuzzy set theory with fuzzy logic the set membership values can range (inclusively) between 0 and 1, in fuzzy logic the degree of truth of a statement can range between 0 and is not constrained to the two truth values {true(1), false(0)} as in classic propositional logic[Novak et al.(1999)].

Fuzzy models have been used in the past for various indices. For example, Water Quality index- a model to Decision Support System to evaluate the river pollution. Another example of a fuzzy model is National Research Council of Canada’s use of fuzzy logic for development of a of synthetic evaluation technique to translate pipe inspection results to condition rating. Further, they used Fuzzy Markov model to plan renewal of large diameter water main pipes. Fuzzy models can be useful in the calculation of predictability and Condition Assessability indices [Rajani et al (2006), Kleiner et al (2005)].

An Artificial Neural Network (ANN), also called a simulated neural network (SNN) or commonly just neural network (NN) is an interconnected group of artificial neurons that uses a mathematical or computational model for information processing based on a connectionist approach to computation. In most cases an ANN is an adaptive system that changes its structure based on external or internal information that flows through the network. Artificial neural networks mimic the ability of the human brain in predicting patterns based on learning and recalling processes[Al-Barqaei and Zayed(2006)].The ANNs are useful for data-based hypothesis development in areas where casual relationships among variables are unknown [Sadiq et al.(2004)].

But, however, in the initial development stage of the indices it might be laborious and would need extensive research for implementation of fuzzy models or neural network in development of predictability and Condition Assessability indices.

Calculation Methodology used in Predictability Index

Therefore, considering the existing literature and study on similar indices, the predictability index calculates using an ***arithmetic mean***. And to ***avoid eclipsing***, if any value is indicating a higher likelyhood of failure, the index thus calculated will indicates a high likelyhood of failure. The lead-time contribution of a factor is taken into account when the factor reiterates itself through the calculations. This logic is explained in Figure 5.

$$I = \text{Max}(s_1, s_2, s_3, \ldots s_n) \qquad \text{If Max}(s_1, s_2, s_3, \ldots s_n) > 3$$

$$= \sum_{i=1}^{N} w_i s_i \qquad \text{If Max}(s_1, s_2, s_3, \ldots s_n) <= 3$$

Where
I= aggregate index
N= number of sub-indices
w_i= *i*th weight
s_i= *i*th sub-index
The weights w_i indicate the relative importance s_i

$$1 = \sum_{i=1}^{N} w_i$$

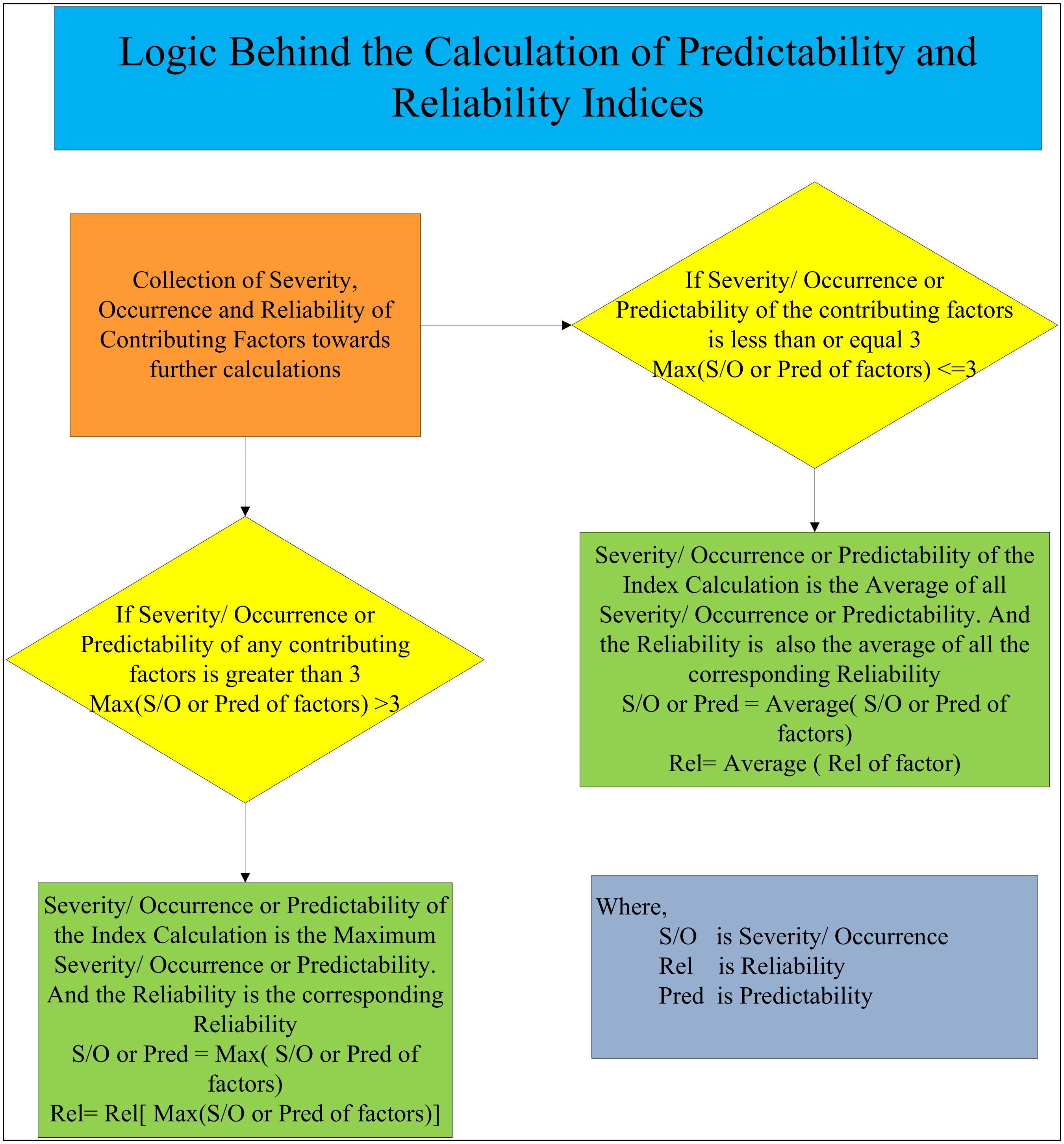

Figure 5. Detailed Logic for the calculation of the Predictability and Reliability Indices

Condition assessment technologies

The Water pipe infrastructure systems need evaluation at regular intervals to ensure proper functioning of the system. Wide range of technologies are used for achieving the condition assessment of these pipelines. The choice of technique is dependent on various factors like the pipe material, diameter, etc. While gathering information regarding the technologies, the main considerations kept in mind for decision-making were pipe material, pipe diameter, and maximum range of assessment, inspection range, assessment parameter, advantages and disadvantage of the technology. The list of technologies has been prepared with the help of the vast source of literature available in relevant fields. The literature included some of the AWWA, AWWARF, USEPA reports and technical publications on relevant subjects.

The technologies can be divided into four classes. The four classes are:

1. External Condition Assessment Technologies: External condition assessment technologies are technologies which do not need interruption of the flow to do the assessment of the pipeline system, and the instrument works external to the pipe.
2. Internal Condition Assessment Technologies: Internal condition assessment technologies are technologies which need the instrument to be sent into the pipeline system. Some of these technologies may need interruption of the flow in the pipelines.
3. Other Methodologies for Condition Assessment: Other methodologies for Condition assessment are methodologies which involve evaluating the system as a whole and not particularly the pipe.
4. Emerging Technologies: Emerging Technologies are technologies which are still in development stage in the field of water pipeline infrastructure system.

The research team at Virginia Tech after conducting a detailed review of literature has grouped the technologies in the above-mentioned categories. The technologies have been studied based on various factors like the pipe material they can be applied on, the diameter of pipeline, inspection rate, etc. In addition, the technologies have been listed in the Appendix with a brief description of the technology wherever necessary along with its advantages and limitations. Table 6 shows the list of technologies for condition assessment of water pipes.

Table 6: Technologies for Condition assessment of Water Pipes

Appendix	**Appendix Material**
A	List of Technologies
B	Internal Condition Assessment Technologies
C	External Condition Assessment Technologies
D	Other methodologies for condition assessment
E	Emerging technologies for condition assessment

Evaluation for Condition Assessability Index

For the evaluation of the Condition Assessability of the pipe failure, insight on the economical aspect of the pipe evaluation is equally important in comparison to its technical evaluation. A conceptual estimate is shown below in the Table 7 [Royer, 2005].

Table 7: A Conceptual Estimate of Benefits & Acceptable Costs of Water Main Prevention

A Conceptual Estimate of Economic Benefits & Acceptable Costs of Main Prevention		
Estimate of potential economic benefits	**Value**	**Units**
Length of installed DW mains in the U.S.†	880,000	Miles
Number of main breaks(NMB) each year in the U.S. †	240,000	Breaks/
Fraction (F1) of NMB that are in high consequence category †	0.01	None
Number of high consequence main breaks/year (NHCMB)=F1 (NMB	2400	Breaks/
Average total extra‡ cost(C) of a high consequence main break † ‡ i.e., Total cost above normal main R3	1,000,000	$
Total Annual Cost of High Consequence MB (CHCMB) = NMB (F1 (C	2.400e+09	$/Yr
Fraction (F2) of NHCMB that are prevented by improved SIM †	0.2	None
Number of prevented high consequence (NP-HCMB) = NHCMB (F2	480	Breaks/
Total Annual Benefit of Inspection (BINSP)=NHCMBF1 (F2 (C	**4.80e+08**	**$/Yr**
Estimate of Acceptable Cost of Inspection for High Risk Mains	**Value**	**Units**
Average total extra cost of a high consequence main break (C)†	1,000,000	$/HC br
Average probability of HC main break (PHCMB) is same as average break from (Kirmeyer, 1994) †	0.27	HC brea
Annual extra risk from HC main break (C (PHCMB)	270,000	$/mi/yr
Annual extra risk from HC main break = Breakeven inspection cost = Cb	270,000	$/mi/yr
Acceptable benefit/cost ratio (R)†	5	None
Acceptable inspection cost/mi/yr for HC main = (Cb/R)	**54,000**	**$/mi/yr**
† Assumptions		

CHAPTER 3. DEVELOPMENT OF PROCEDURE FOR CALCULATING PREDICTABILITY AND CONDITION ASSESSABILITY INDICES

The aim of this research is to explore the feasibility and value of developing procedures for calculating predictability and condition assessability indices for selected high-risk water mains. The predictability index can be defined as the inherent, theoretical predictability of selected key types of structural failure. Whereas the condition assessability index will indicate the technical and economical feasibility of preventing selected key structural key failure types.

Predictability Index calculation is not something new to the industry. This index has been calculated for various other purposes like climate predictability, etc. However, this is the first attempt to calculate predictability of pipe failure. This section clearly explains the procedure followed by the research team in deriving the methodology for calculation of predictability and condition assessability index. The procedure involves deep understanding of the pipe system, various pipe materials and their failure modes. There is also a need for understanding the various technologies and methodologies presently being used or/and being developed in the industry.

Procedure for calculation of Predictability Index

For the calculation of the predictability index, one might ideally have to go through the following stages:

(i) identify high priority pipe failure types through characterize their mode, mechanism, conditions, and indicators;

(ii) determine whether there are reliable indicators of the onset of failure and lead-time of indicators; and

(iii) develop a predictability score for the selected pipe situations. The following steps describe in detail the development of predictability indices.

Since the predictability index is particular to a certain system, a detailed description and understanding of the system (including the installation procedure followed) is necessary. The steps in which the system can be broken down for understanding the process is described in Figure 6.

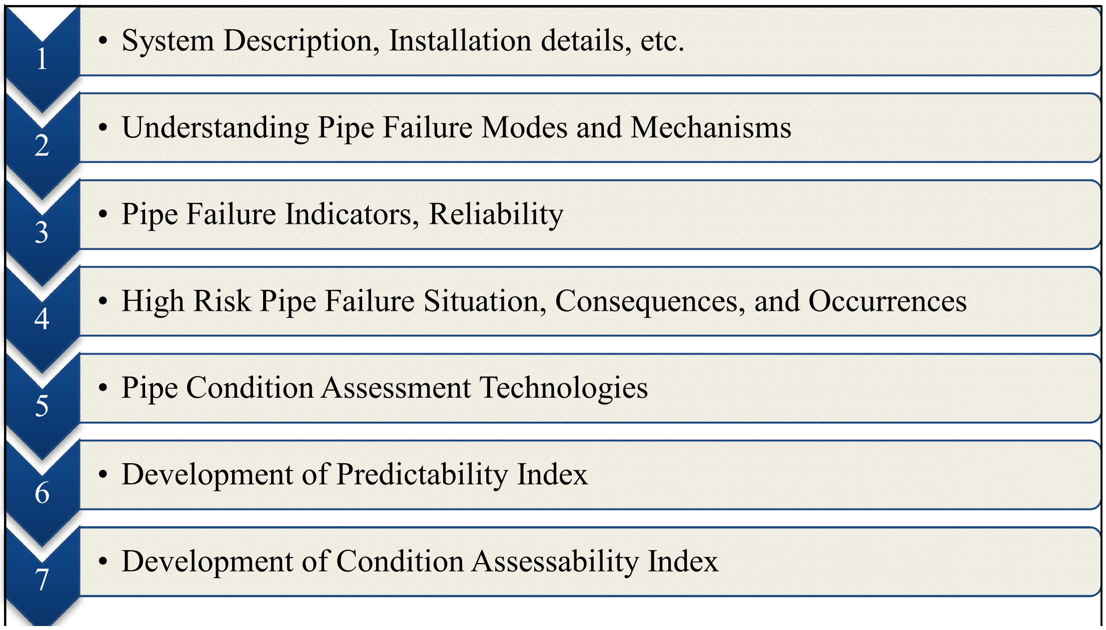

Figure 6: Evaluation of the Pipe System and Failure Analysis

The process of developing the pipe failure predictability index from the primary understanding of the pipe failure mode and mechanism is shown in Figure 7.

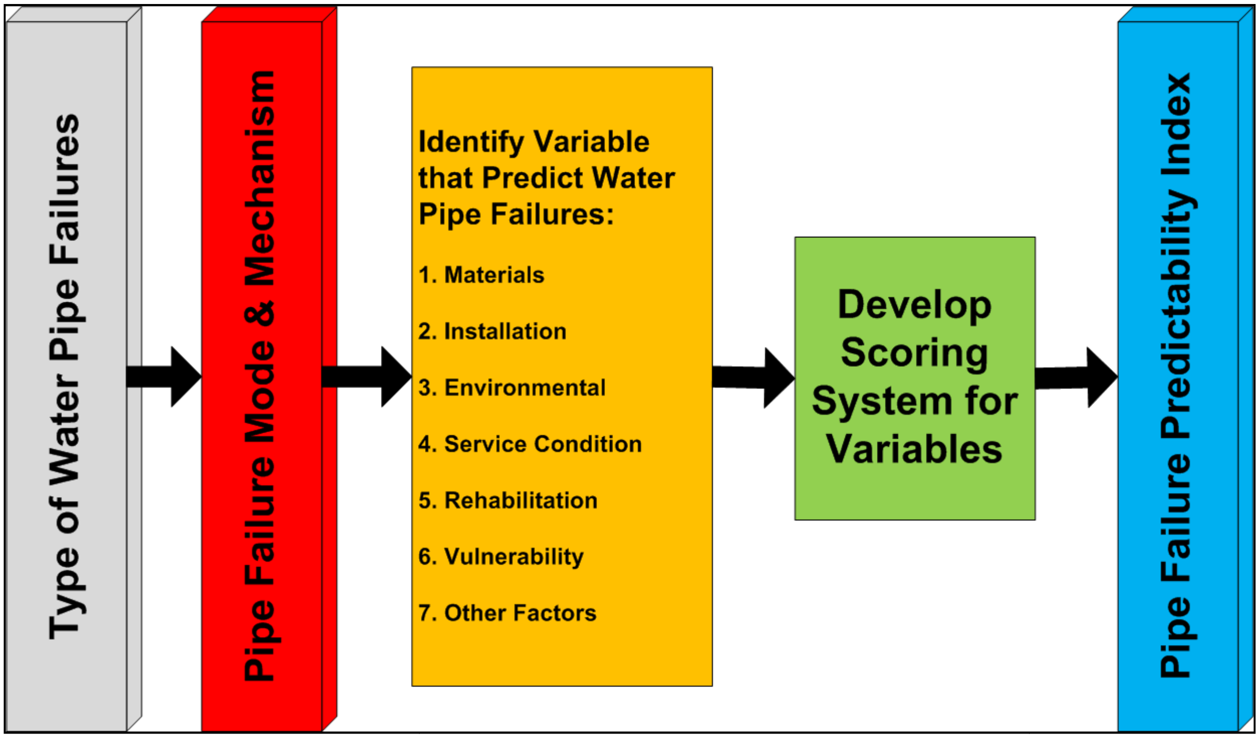

Figure 7: Process for Development of Predictability Index

After developing the predictability index based on occurrence, indicators and lead-time, a case study would be conducted in order to indentify the high-risk pipes. High-risk pipes can be defined based on the circumstances and scenario of the existing pipe.

Step 1: System Description

Understanding the pipe system is the primary requirement for developing the predictability index. Many factors and their corresponding interactions affect the structural failure of the pipe. Therefore, the first step for developing a predictability index starts with understanding the pipe infrastructure data models. Figure 8 shows the various factors that influence the system.

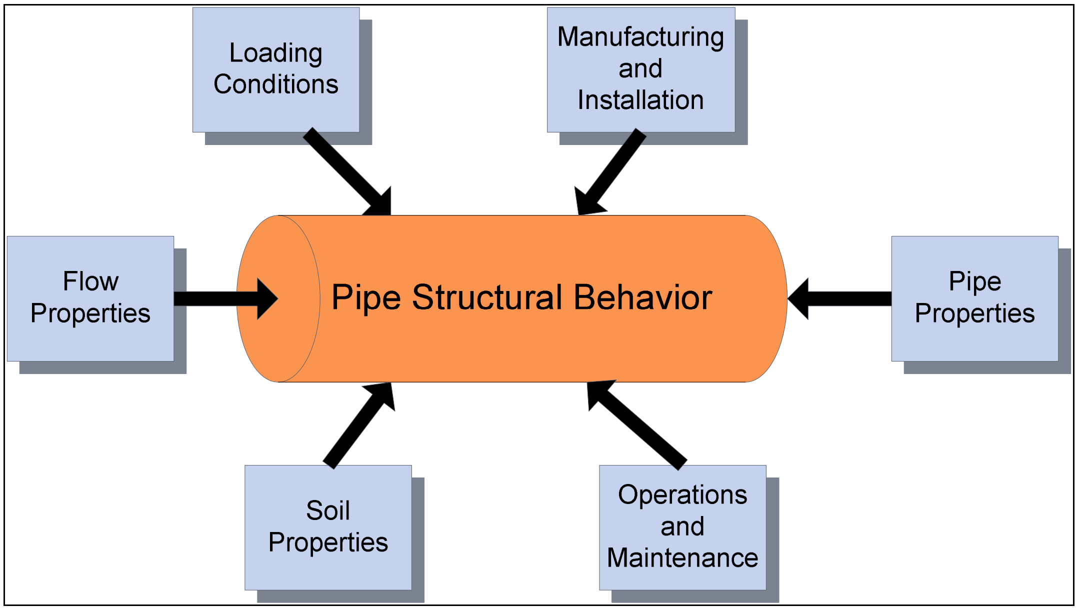

Figure 8: Factors that influence the Pipe Infrastructure System

While classifying the pipe by material and joint type, the pipe system data has to be collected. This includes the installation of the pipe, repairs done and the details of the existing system. The exhaustive data models have identified approximately 80 parameters that can have effect on the condition/performance of the pipe.

Step 2: Understanding Pipe Failure Modes and Mechanisms

The understanding of various pipe materials used in the water pipes is significant for failure analysis and development of the predictability index. The failure processes in buried water pipes are much more complex than expected. Applied forces exceeding the residual strength of the pipe material cause the most basic level pipe failures. In general, the forces applied to buried pipe can be considered as five kinds: those produced by internal pressure; bending forces; crushing forces; soil movement induced tensile forces; and temperature induced expansive forces.

The various materials are Asbestos Cement, Cast Iron, Ductile Iron, Glass Reinforced Plastics, Lead, Prestressed Concrete Cylinder Pipe, Polyethylene, Polyvinyl Chloride, Steel, and Wood. The understanding of various pipe materials used in the water pipes is very important for failure analysis and development of predictability index.

Pipe failure modes and mechanisms within this report are separated into their material type due to differing modes and mechanisms. For example ductile iron (DI) pipes may fail because of corrosion however; corrosion is not present in PVC pipes. Each materials is then classified into failure modes and mechanisms based on the pipe as well as the joint.

Pipe failure mode based on water pipe materials are described in this section.

Asbestos Cement

Asbestos Cement (AC) Pipes were used only in water systems. Asbestos Cement pipes usually undergo lining failure. AC pipes without lining undergo failures like circumferential cracking, longitudinal splits and pipe degradation. The failure modes and mechanisms of main pipes of asbestos cement are shown in Figure 9 and those of the joints are shown in Figure 10.

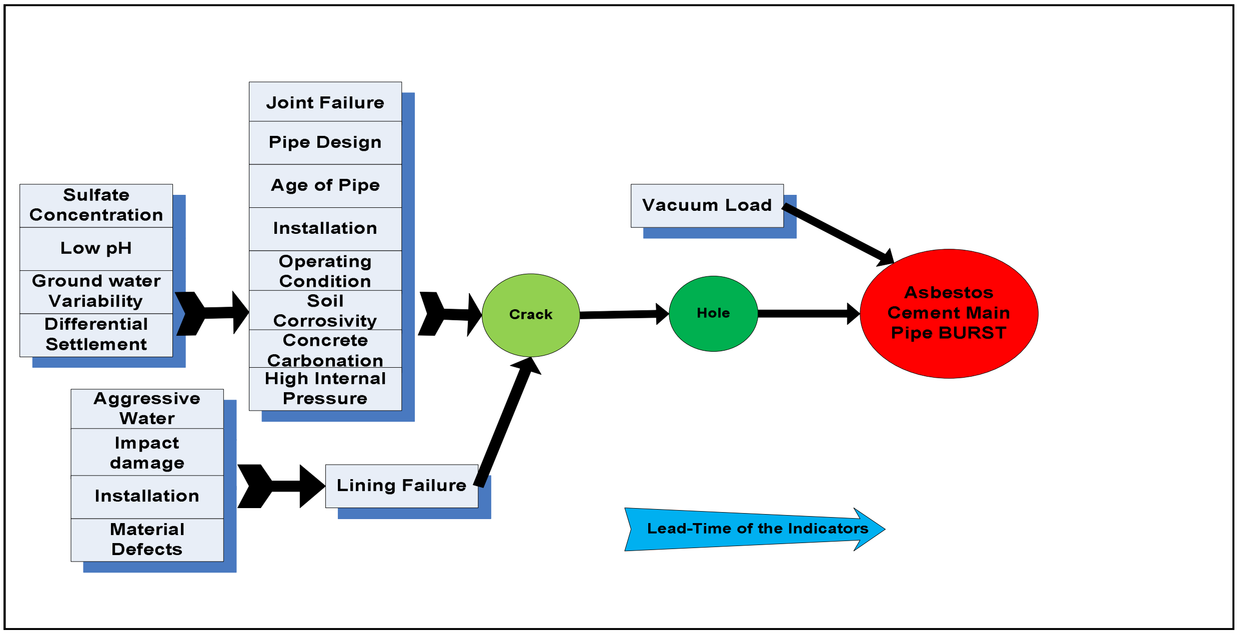

Figure 9: Failure modes and mechanism of asbestos cement pipes

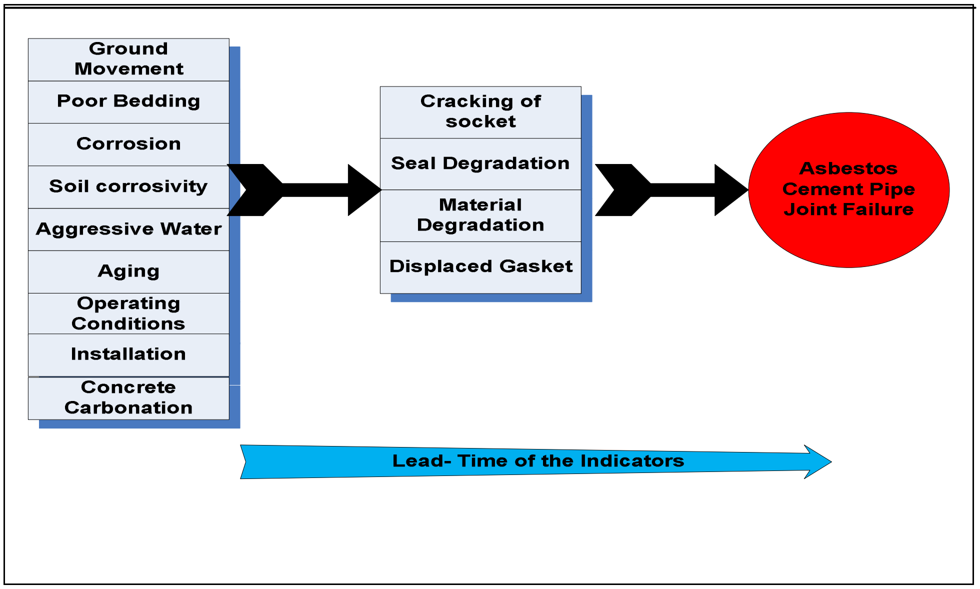

Figure 10: Failure modes and mechanisms of joints of asbestos cement pipes

Cast Iron

Cast Iron (CI) pipes were installed for water distribution and transmission system. Cast iron pipes usually crack first and corrode through holes. The detailed study of the failure modes and mechanisms of the cast iron main pipes is shown in Figure 11 and the failure modes and mechanisms of the joints of cast iron pipes is shown in Figure 12.

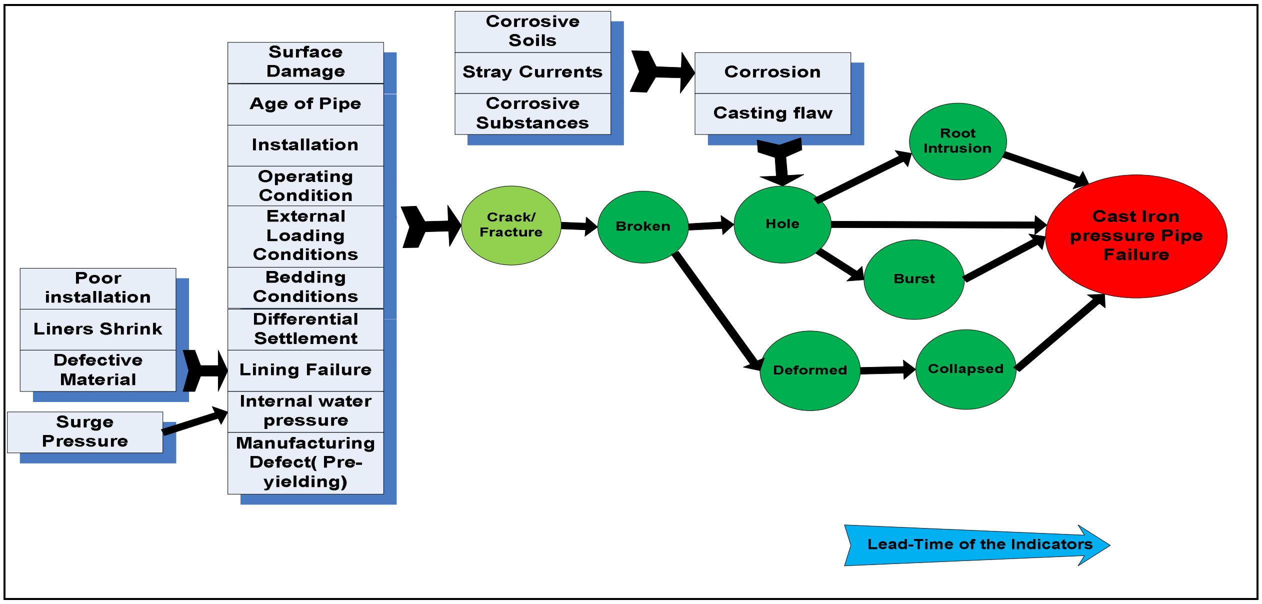

Figure 11: Failure modes and mechanisms of cast iron main pipes

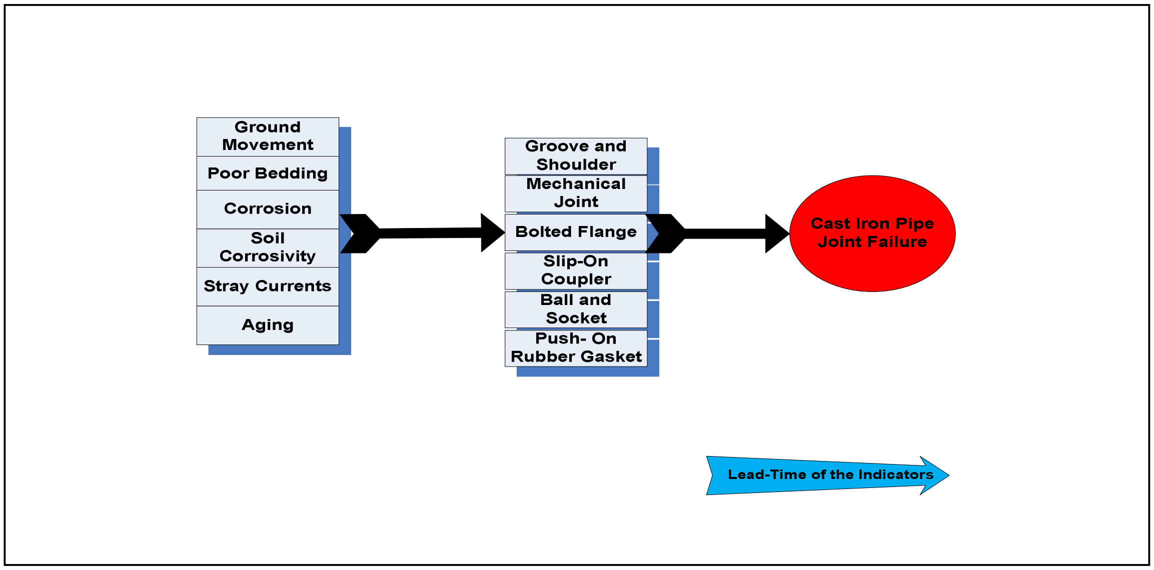

Figure 12: Failure modes and mechanisms of joints of cast iron pipes

Ductile Iron

In Ductile Iron pipes primarily, corrosion governs the failure of ductile iron pipes. This is illustrated in Figure 13 and Figure 14.

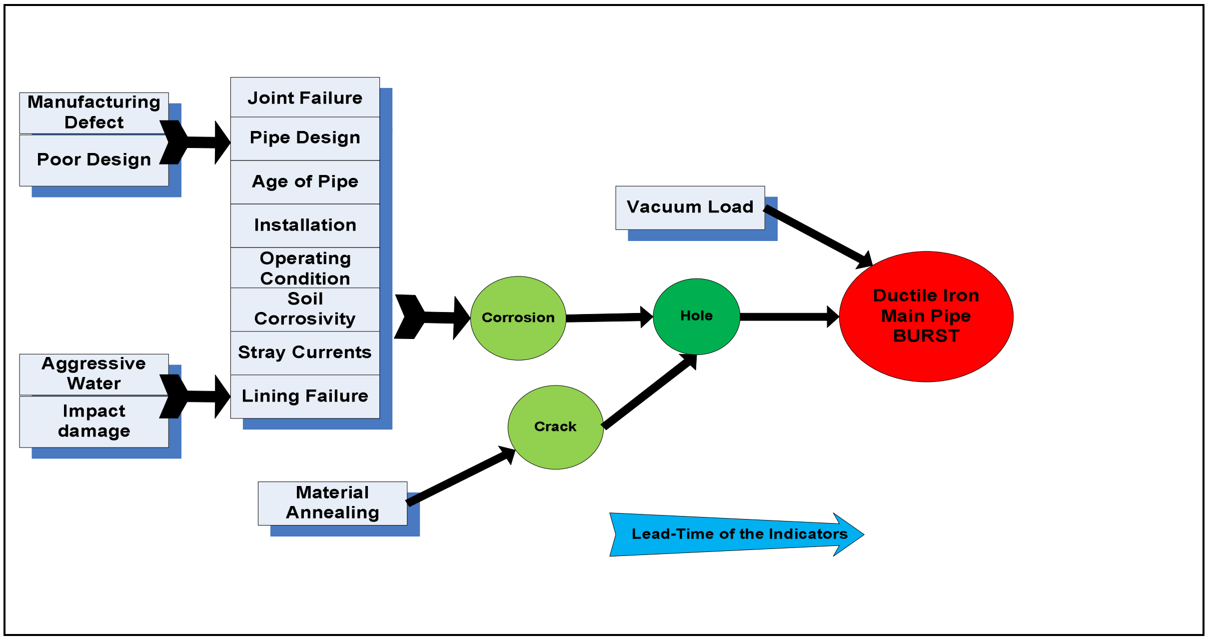

Figure 13: Failure modes and mechanisms of the ductile iron main pipe

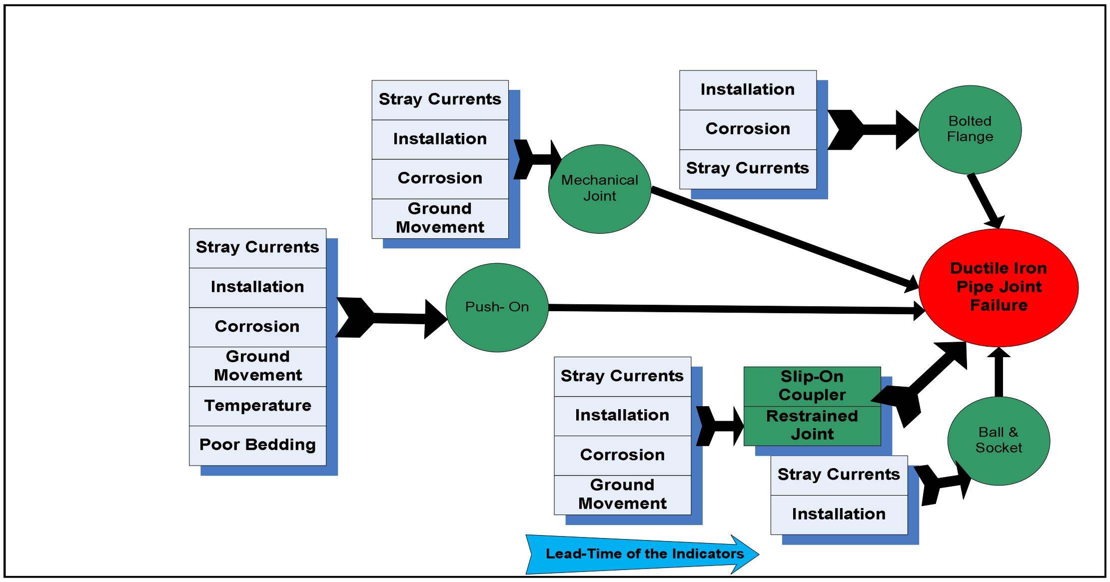

Figure 14: Failure modes and mechanisms of the joints of ductile iron pipes

Glass Reinforced Plastics

The main failure mode for the Glass reinforced plastic pipes is lining failure. The failure of the main pipe is illustrated in Figure 15 and those of the joints in Figure 16.

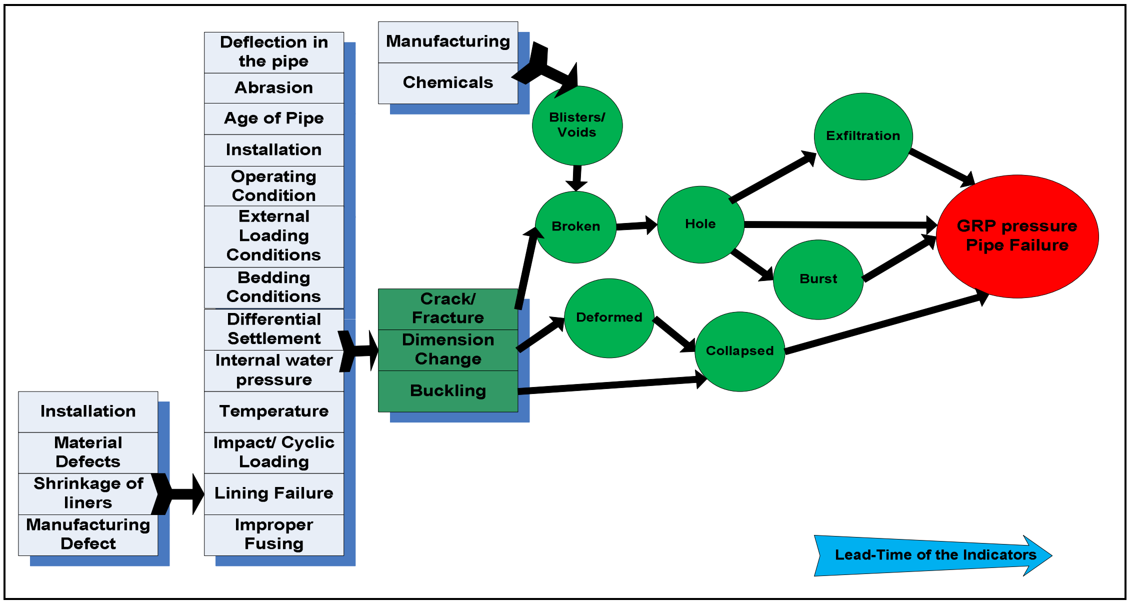

Figure 15: Failure modes and mechanisms of GRP pipes

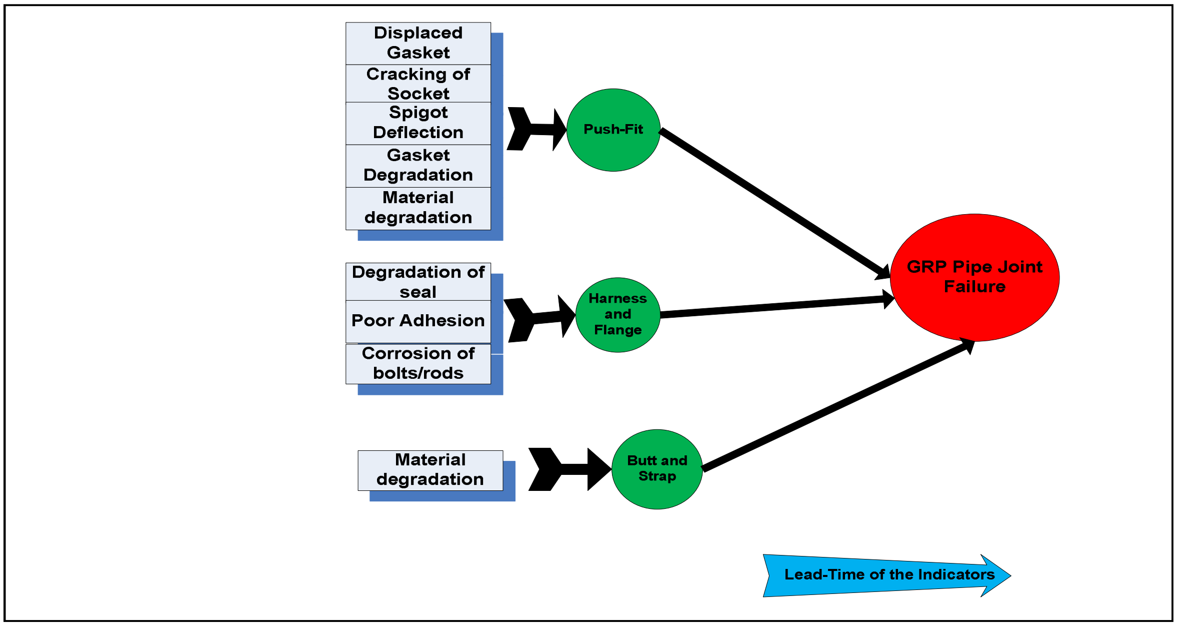

Figure 16: Failure modes and mechanisms of joints of GRP pipes

Lead

Lead pipes were mainly installed as water mains. The failure modes and mechanisms have been illustrated in Figure 17 for the main pipes.

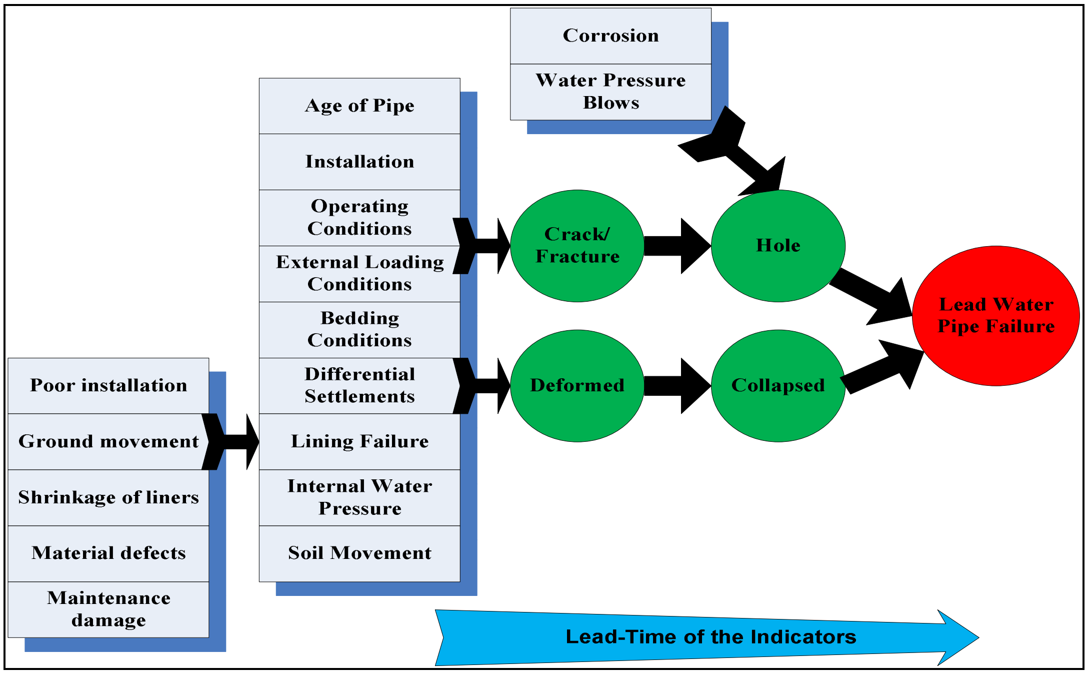

Figure 17: Failure modes and mechanisms of lead water pipes

PCCP

Pre-stressed Concrete Cement Pipe (PCCP) is a commonly used pipes in the water industry. Wire breaks and concrete failure are the prominent failure modes for PCCP. The failure modes and mechanisms of the main pipes are shown in Figure 18 and that of the joints in Figure 19.

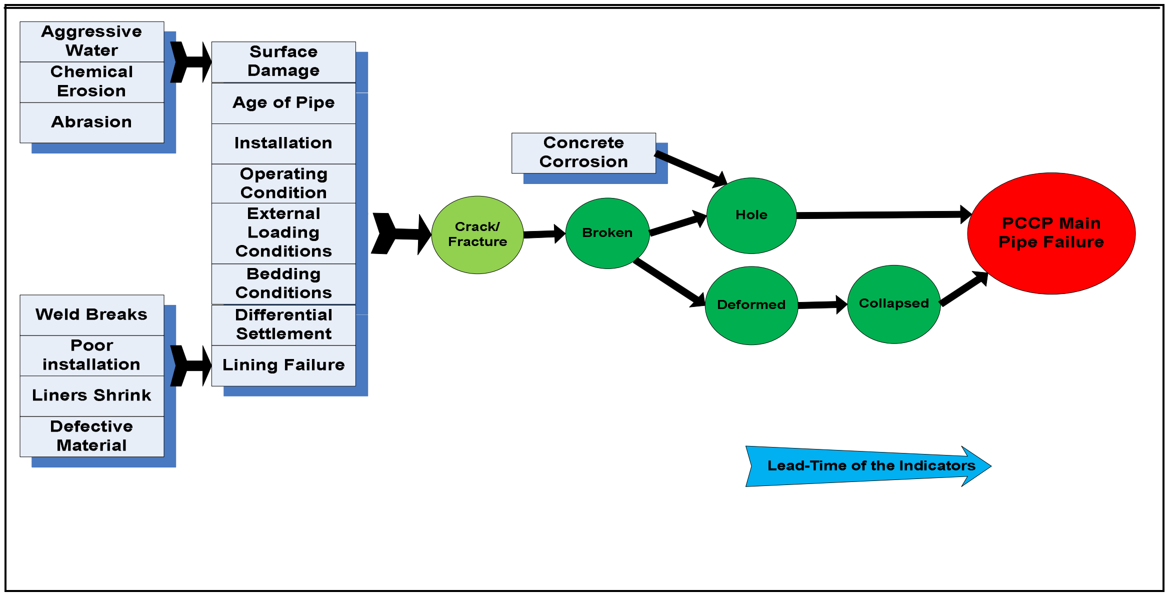

Figure 18: Failure modes and mechanisms of PCCP main pipes

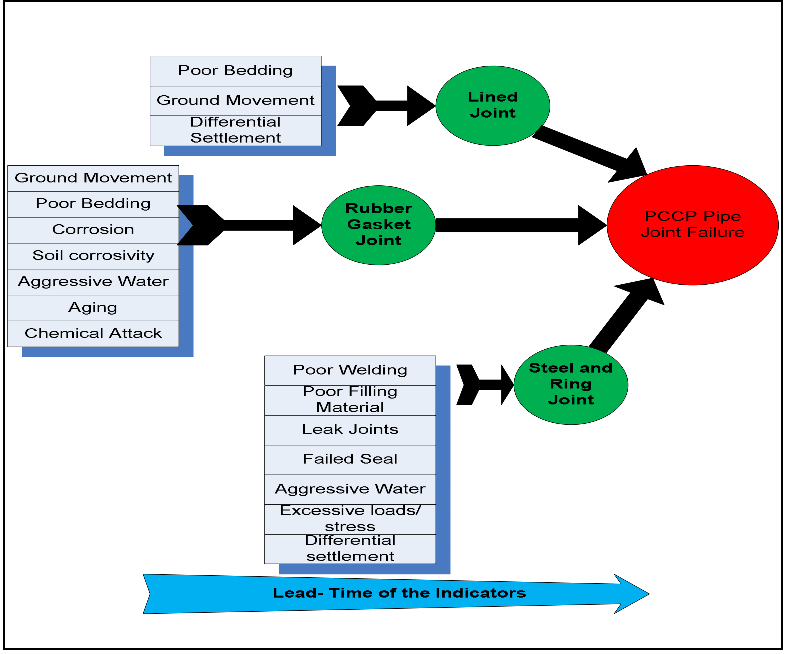

Figure 19: Failure modes and mechanisms of the PCCP pipe joints

Polyethylene/ Polyvinyl chloride

The failure properties of Polyvinyl chloride and polyethylene pipes are illustrated in Figure 20 and Figure 21.

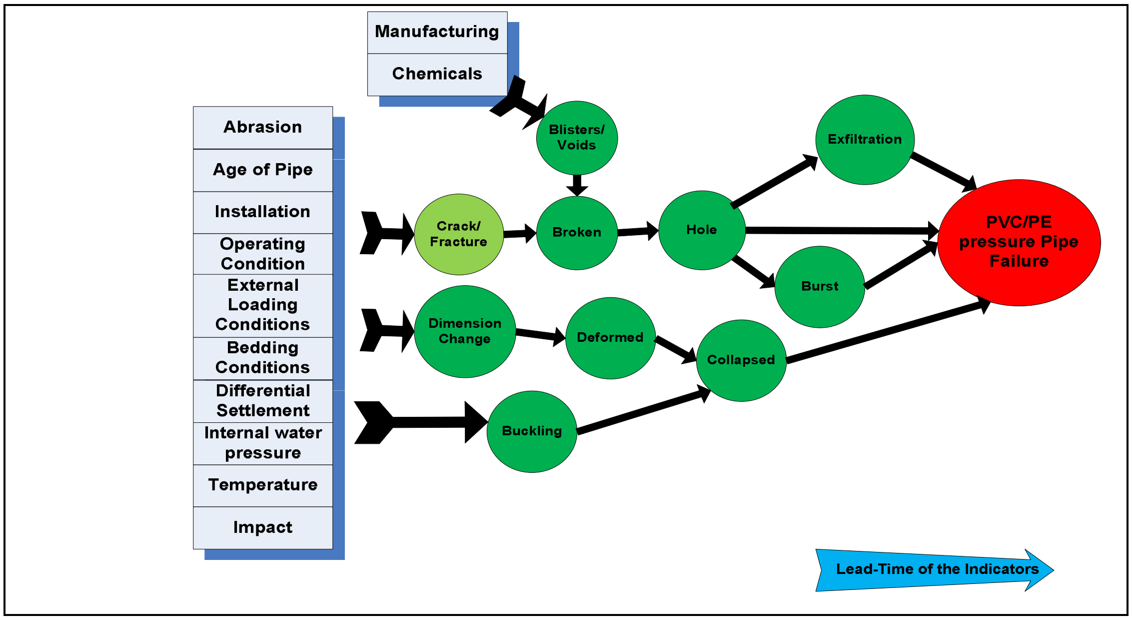

Figure 20: Failure modes and mechanisms of the plastic pipes

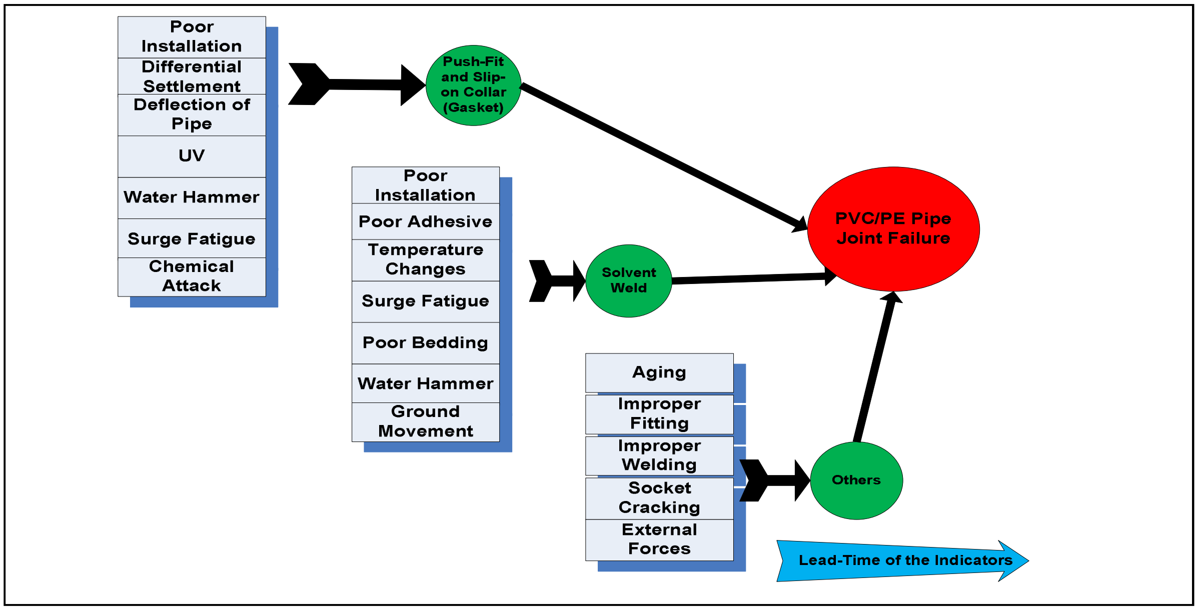

Figure 21: Failure modes and mechanisms of the plastic pipe joints

Steel

Steel pipes are mainly used as the pressure pipes. Welding failure, corrosion, cracks are the major failures of the steel pipes. The failure modes and mechanisms are illustrated in Figure 22 and Figure 23.

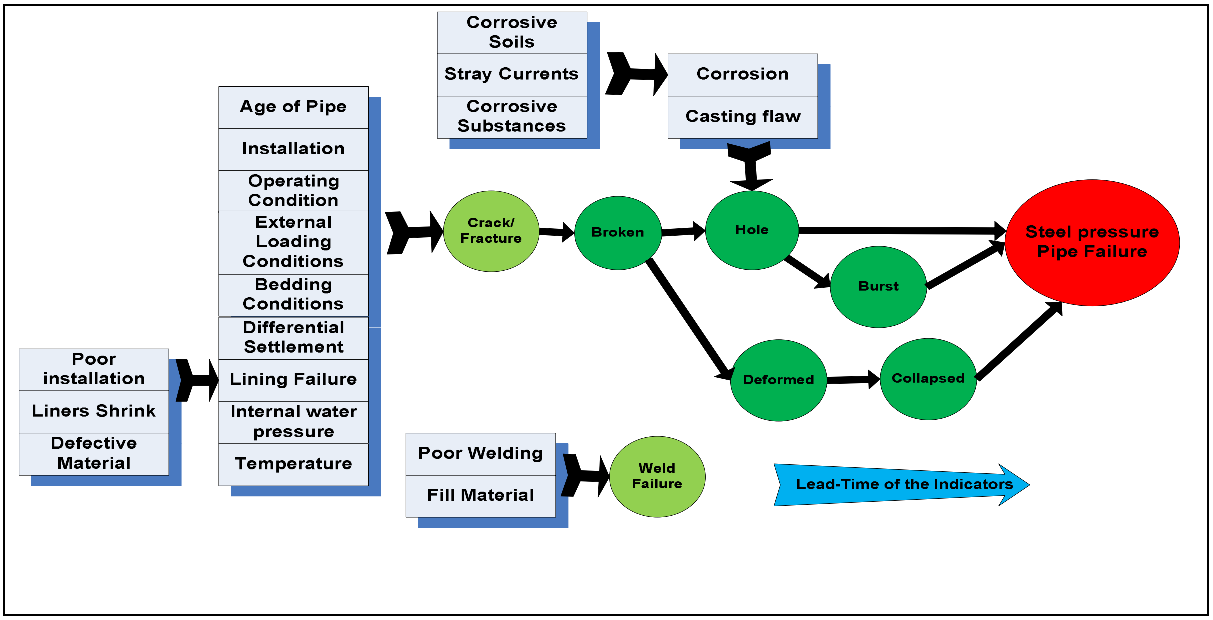

Figure 22: Failure mode and mechanism of steel pipes

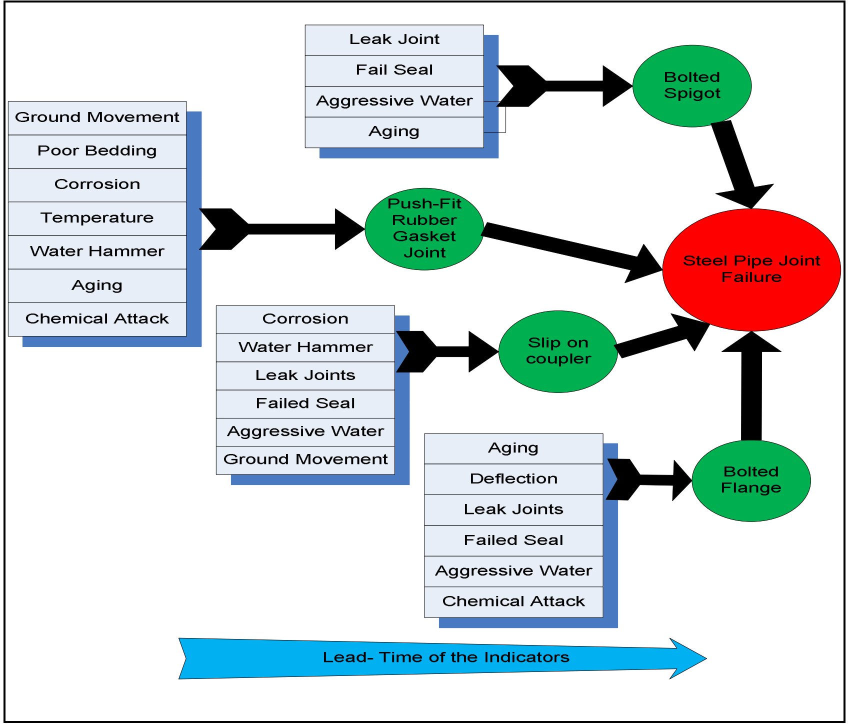

Figure 23: Failure modes and mechanisms of the steel pipe joints

Wood

Wood pipes were used for water pipes in few utilties. Wood pipe primarily fail through cracks. The failure of wood pipes is illustrated in Figure 24.

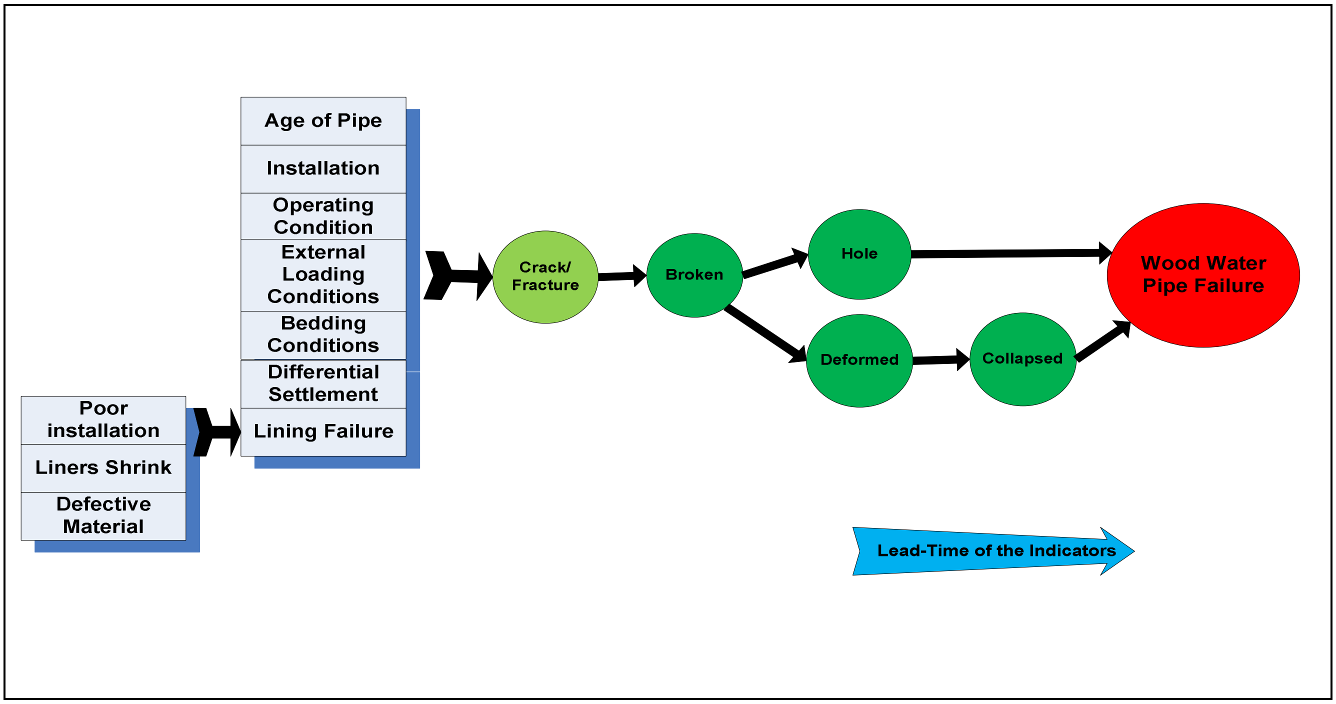

Figure 24: failure modes and mechanism of wood pipes

Step 3: Pipe Failure Indicators, Reliability and Lead Time

Each failure mechanism has some indicators and data associated with the indicators. By understanding the system, one can derive the relevant data required for understanding the life of the system and the types of failure faced by the system. We would also need an understanding of the cause-effect scenario that will be created by each of the failures before we derive the condition-time relationship of the pipe. The various causes and the indicators that are possible in general for all pipe types are listed below and the graphical description is illustrated in Figure 25. Figure 25 includes repair and rehabilitations since they have equal importance as installation and might cause failure before the actual lifetime if the pipe is not repaired properly.

Typical Factors Contributing to Pipe Failure

- Operational Condition
- Design Parameters
- External Loads
- Internal Loads
- Temperature Change
- Loss of Bedding Support
- Pipe Properties
- Others

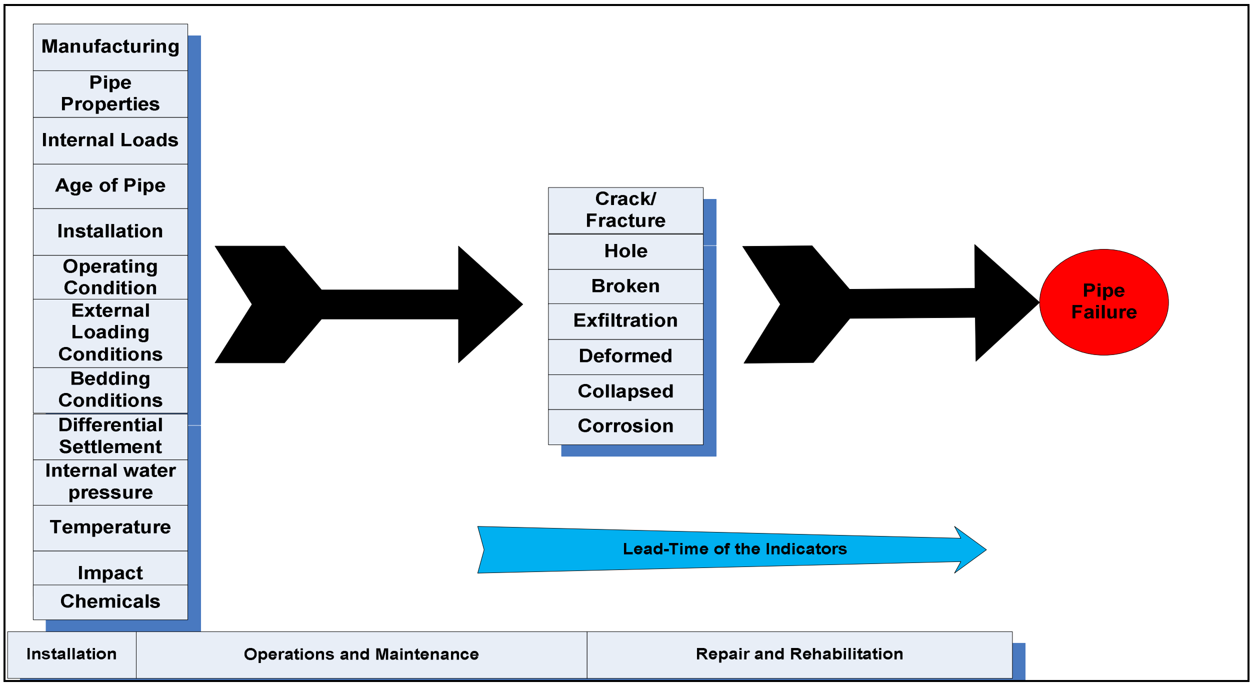

Figure 25: Factors contributing to the major pipe failures faced by various pipes

Typical Pipe Failure Indicators

- Leak that causes erosion
- Soil movement that causes excess strain
- Increasing leak rates
- Excessive wall thinning
- Pipe Condition
- Joint Condition
- Others

The Figure 26 shows an example of the condition of a pipe against time. A failure mode may change the slope in the graph and each failure mode may have some indicators. And this change in slope is dependent on the existing conditions of the pipe and the associated lead time towards failure. Without the knowledge of the lead time the prediction model will not be accurate. From the graph shown in Figure 26, we can derive the data relevant to assess the failure mode.

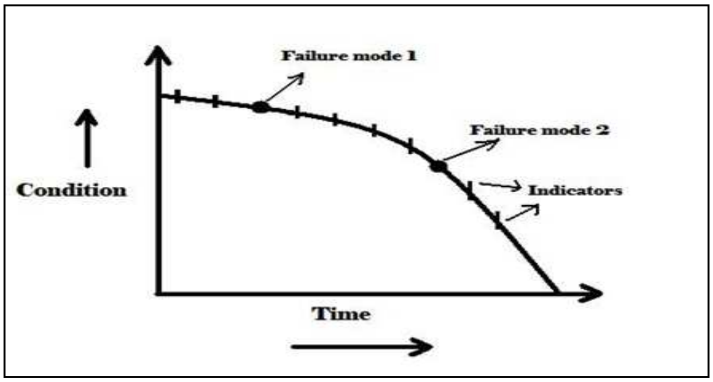

Figure 26: Pipe Failure Modes and Indicators

From the failure mode and mechanism diagrams derived in this section we can arrive at various ways the pipe can fail. This phase of work is still in development.

Step 4: High Risk Pipe Failure Situation and Water Quality

The probability of occurrence of these failure modes need to be evaluated for future analysis. The environment in which the pipe exists is essential to predict its failure and the impact of the failure on the surrounding environment. The high-risk situations for pipelines are the situations of the pipe existence which have higher probability of failing. The high-risk pipe situations are listed below.

- Proximity to a liquefaction area
- Proximity to a landslide prone area
- Proximity to a pipe surface damaging chemicals
- Potential exposure to corrosion
- External loading scenario

- Differential settlement
- Extreme temperature
- Water quality
- Others

Procedure for calculation of Condition Assessability Index

The pipe failure Condition Assessability index is similar to the predictability index, but it takes into account the capability of existing (or innovative) condition assessment technologies/methodologies for measuring the monitoring the deterioration process. Economic feasibility and cost may be added as a further refinement.

The first stage for development of pipe failure Condition Assessability index is understanding the pipe failures and distress indicators along with development of understanding of the condition assessment technologies that identify these failures and distress indicators. The performance assessment and economic analysis of the condition assessment technologies should be performed to develop a scale for the Condition Assessability Index. Figure 27 explains the methodology for development of Condition Assessability index.

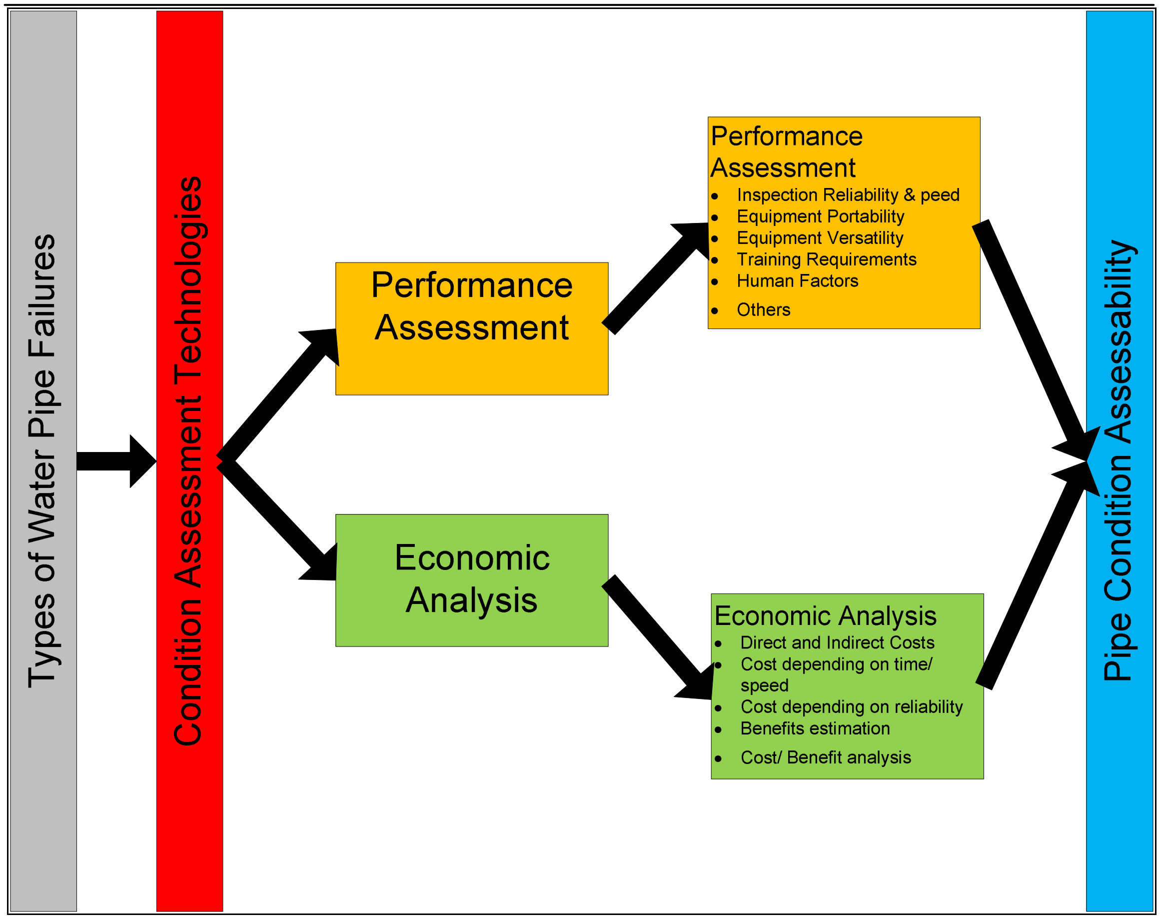

Figure 27: The evaluation of Condition Assessability index

The procedure for calculation of Condition Assessability index required knowledge of the following things

1. Pipe Condition Assessment Technologies/ Methodologies
2. Relating various failure modes with the technologies/ methodologies which can detect them
3. Economic Strategies

Relationship between the predictability and condition assessability index

The Relationship between the predictability and condition assessability index of the pipe failure is described below in Figure 28 and Figure 29.

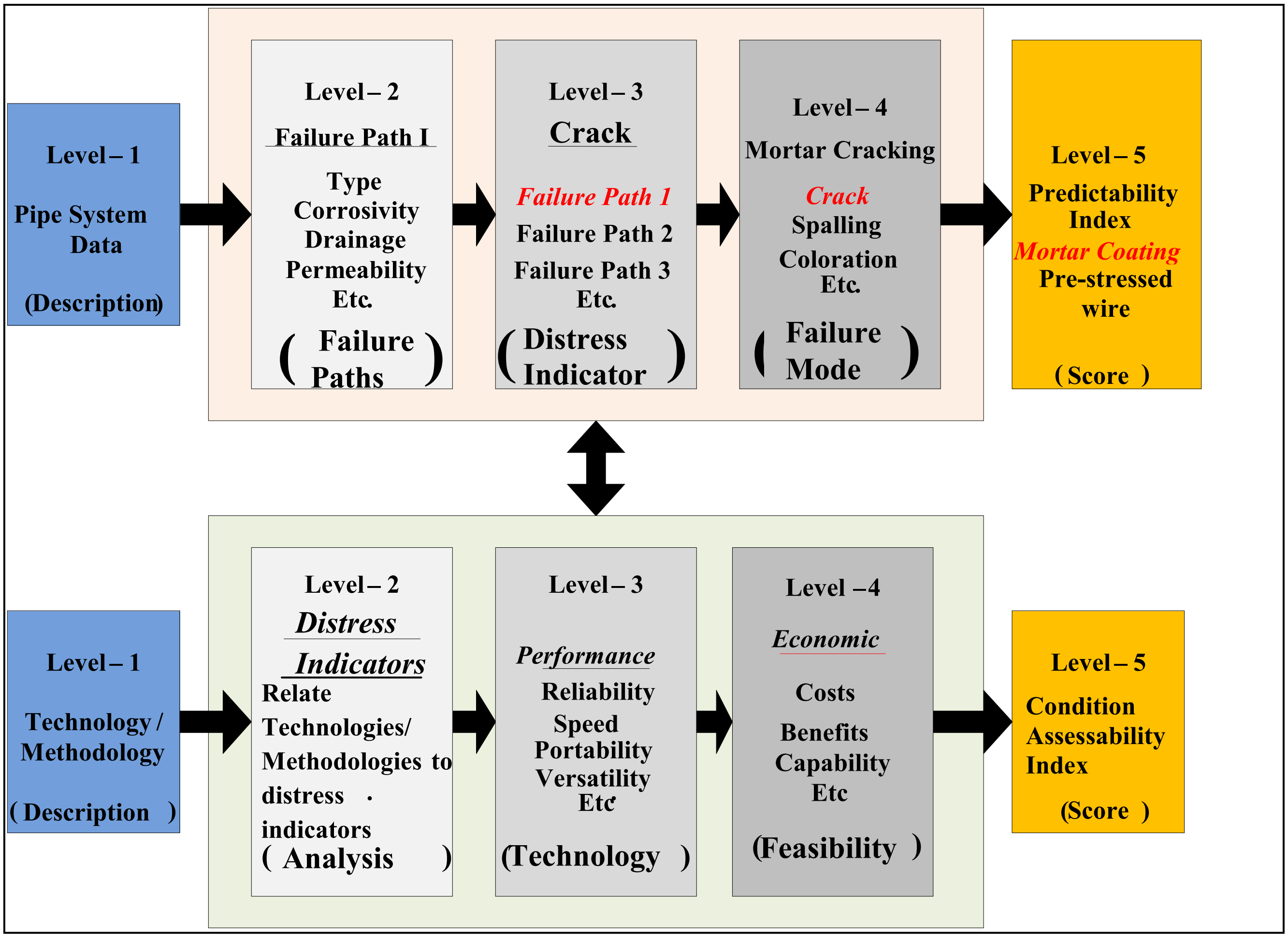

Figure 28: Development of Predictability and Condition Assessability Indices

Figure 28 explains the relationship between the predictability and Condition Assessability indices from the methodology stage. The inter-relation between the two indices is the distress indicators and the data parameters. For the calculation of the predictability index, the data parameters and distress indicators are linked relative to the failure mechanism governing the material. In case of the Condition Assessability index, the distress indicators and data parameters are evaluated by their nature of failure detect-ability with the knowledge of technologies and methodologies present.

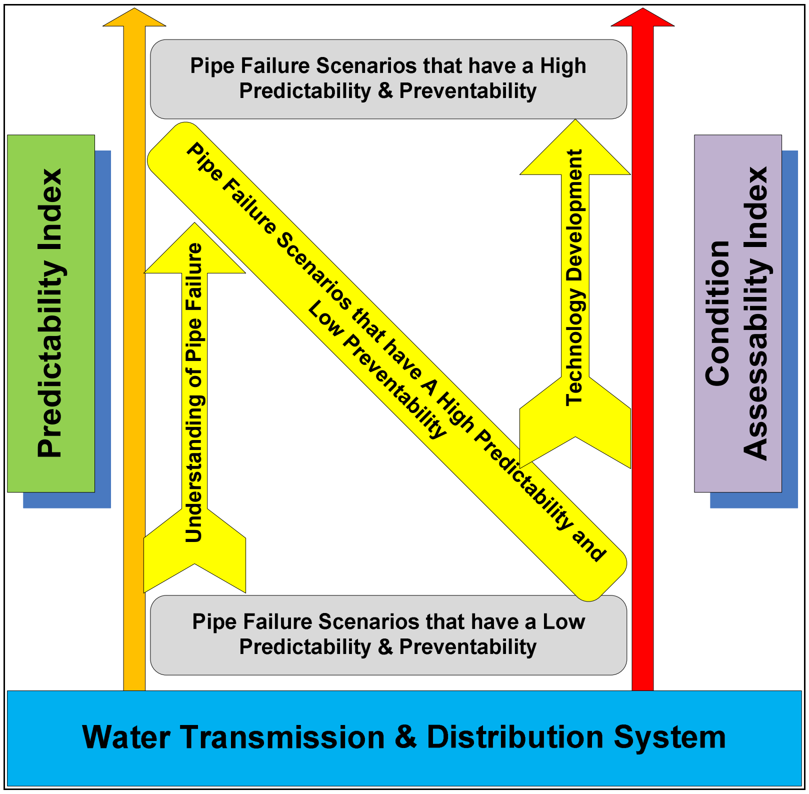

Figure 29: Relationship between Predictability and Condition Assessability Indices

The values of predictability and Condition Assessability indices hence obtained are going to provide guidelines for the utility to understand their pipeline system effectively. Low predictability and low Condition Assessability is a case, which required the utilities to understand their system better. This is both in terms of the data parameters to be collected and in terms of technologies for failure mode detection. Low predictability and high Condition Assessability might be a close to ideal case, where the pipe has low risk of failure and the Condition Assessability is high. High predictability and high Condition Assessability is also a confidence situation for the utilities as they are both aware of the high- risk situation faced by their pipelines and also the technologies/ methodologies which might be of help for them. High predictability and low Condition Assessability is an unwanted state for the pipe, where the pipe is identified to be in high risk but there does not exist sufficient technologies or methodologies for preventing the pipe failure and associated consequences.

CHAPTER 4. METHODOLOGY TO CALCULATE PREDICTABILITY INDEX

The relevant data for a failure mode pertaining to a pipe system have been derived in the earlier stages. The predictability index can be evaluated from parameters based on the stage of the pipe life it can be collected namely installation parameters, manufacturing parameters, operational/ maintenance parameters, and other parameters as shown in Figure 30.

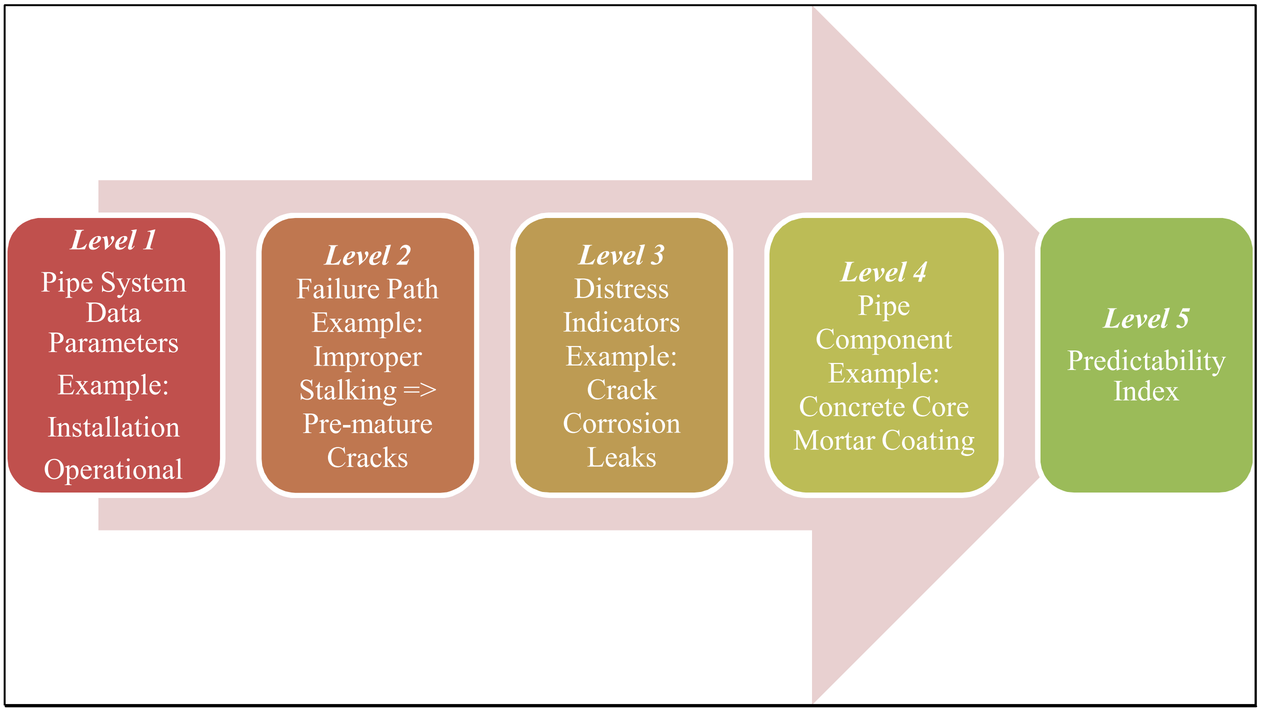

Figure 30: Process for Development of Predictability Index

The predictability index depends on the data collected by the utilities. However, there is a high possibility that the utility does not possess all the data required for the evaluation of the index. Hence, the index is divided into two indices. One evaluates the severity and occurrence of the factor and its contribution towards the distress indicators. . And the second part of the index helps evaluate the reliability of this index depending on the data available and confidence in data.

The process of deriving the predictability index is divided into 4 stages. The input has to be added in the first stage as the pipe system data required and the reliability associated with the input data.

Stages of Calculation of Predictability Index

Stage 1:

Stage 1 consists of factors that influence the pipe performance. Each influencing factor is described in the table along with its possible unit and range of the factor. The utilities would need to input the source of the data. ***Microsoft Excel Spreadsheet is used to evaluate the severity and reliability of the data with the help of in-built formulae and equations***. Figure 31 shows the severity/ occurrence and reliability of the influencing factors from the data input.

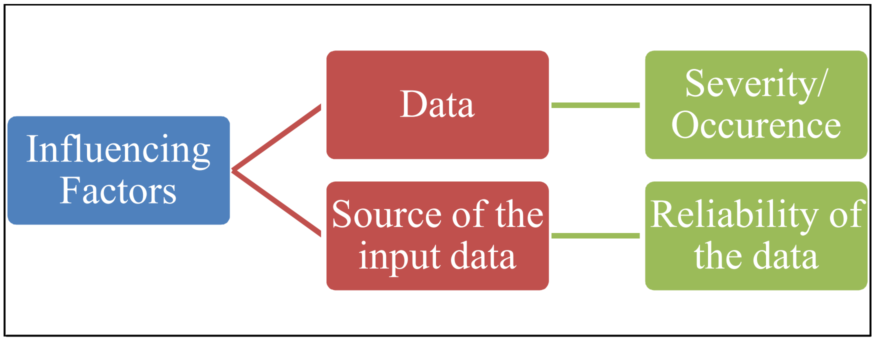

Figure 31: The Severity/Occurrence and Reliability Evaluation from initial data

Stage 2:

In the second stage, the influencing factor's weights towards each of the possible failure path have been indentified and the severity/occurrence of the failure paths is calculated along with the reliability of the data as shown in Figure 33. The logic for this calculation is shown in Figure 33. The Severity/ Occurrence are evaluated on statistical weighted averages and the reliability is evaluated on the concept of theory of evidence, which does not consider 100% presence of data/knowledge towards the evaluation.

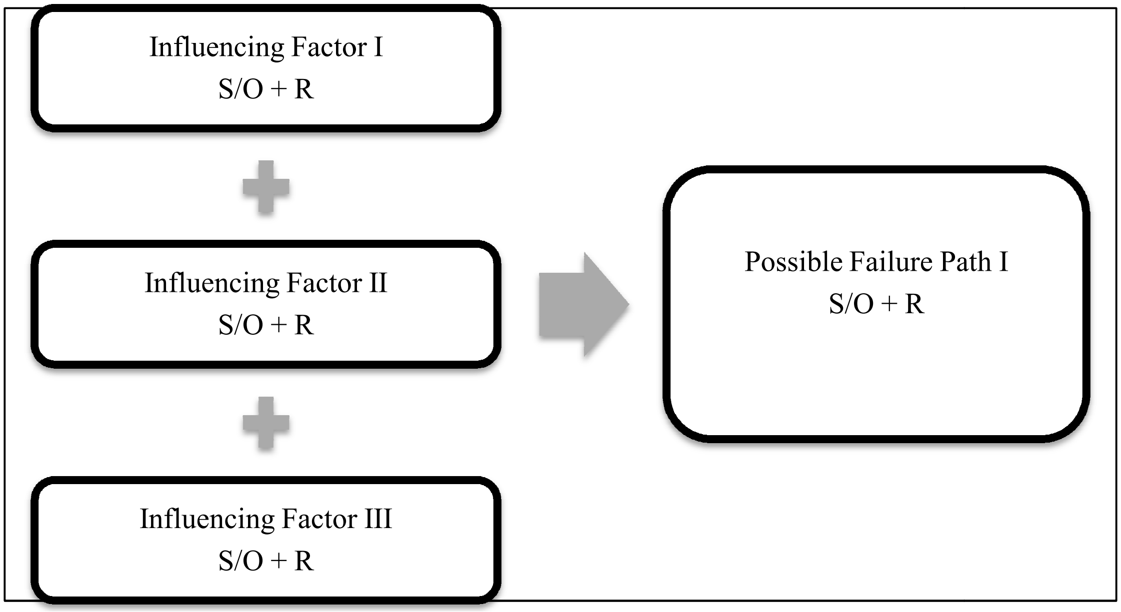

Figure 32: The relations between influencing factors and the possible failure paths

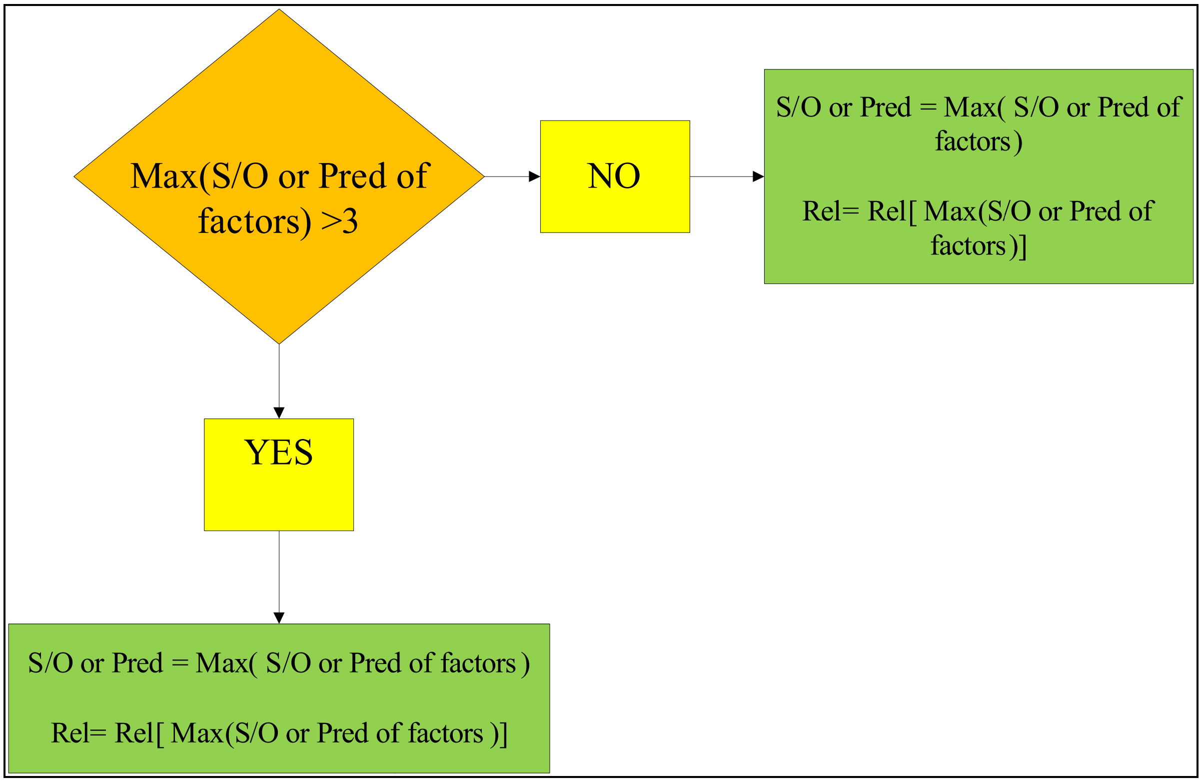

Figure 33. Logic behind the Severity/ Occurrence and Reliability Calculations for Failure Paths

Stage 3:

Various Failure paths can lead to the same distress indicator. The probability of the distress indicator that can be caused by a particular path will be variable and depends on particular situation. Figure 34 illustrates this stage.

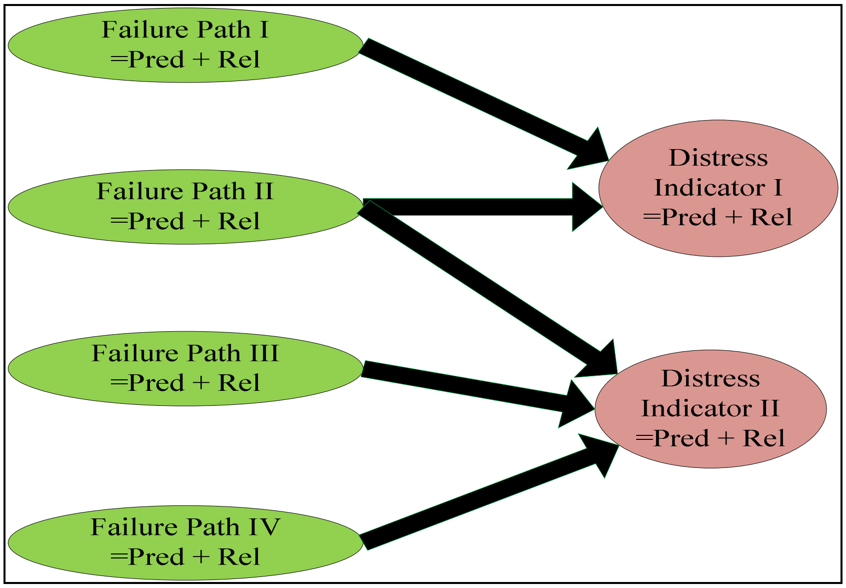

Figure 34: The Distress Indicators and Failure Paths Interdependency

Stage 4:

The various distress indicators are divided as per the failure mode, i.e. crack, corrosion, joint failure, deformed pipe and leaks. These are evaluated from the severity/occurrence and reliability of the various distress indicators that can be caused by the given circumstances. The basic logic considers a weighted average for the predictability from the severity/occurrence of the distress indicators, as illustrated in Figure 35.

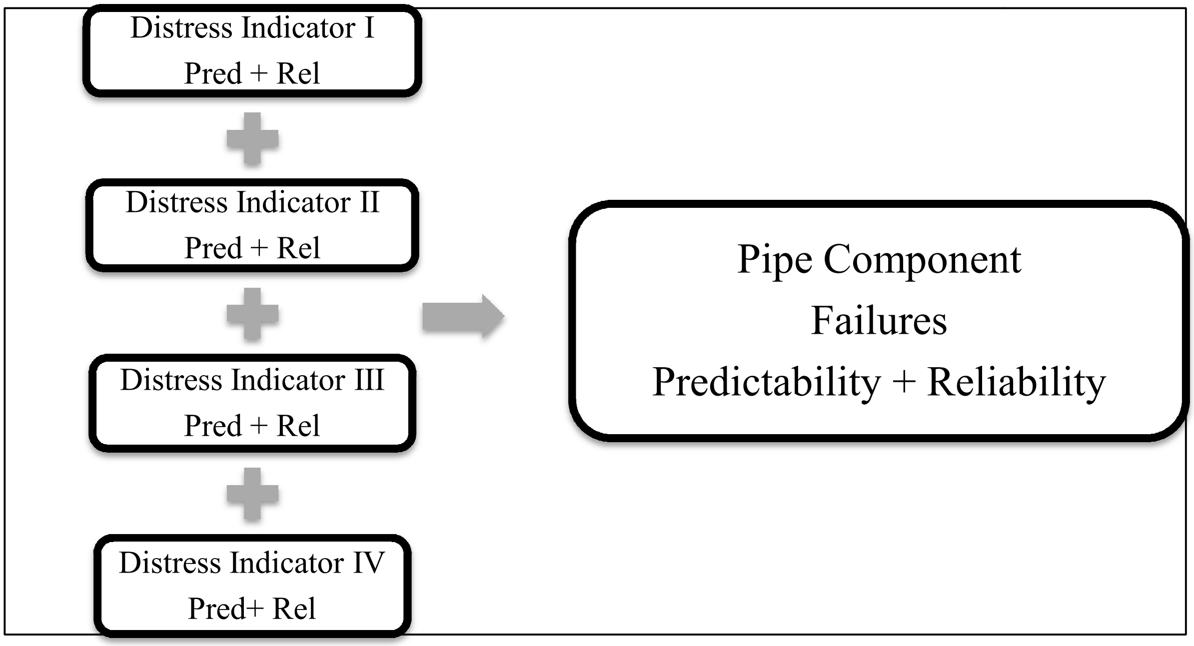

Figure 35: The relationship between distress indicators and the pipe component failure modes

However, if one factor is very severe with a rank 5 or two or more with a severity more than rank 4, would affect the predictability of the concerned pipe section directly.

Stage 5:

The predictability index of the pipe burst is evaluated by the similar logic used for evaluation of the failure mode. The failures of mortar coating, joints, shape, leaks, etc. Figure 36 illustrates the relationship between pipe component failures and pipe failure.

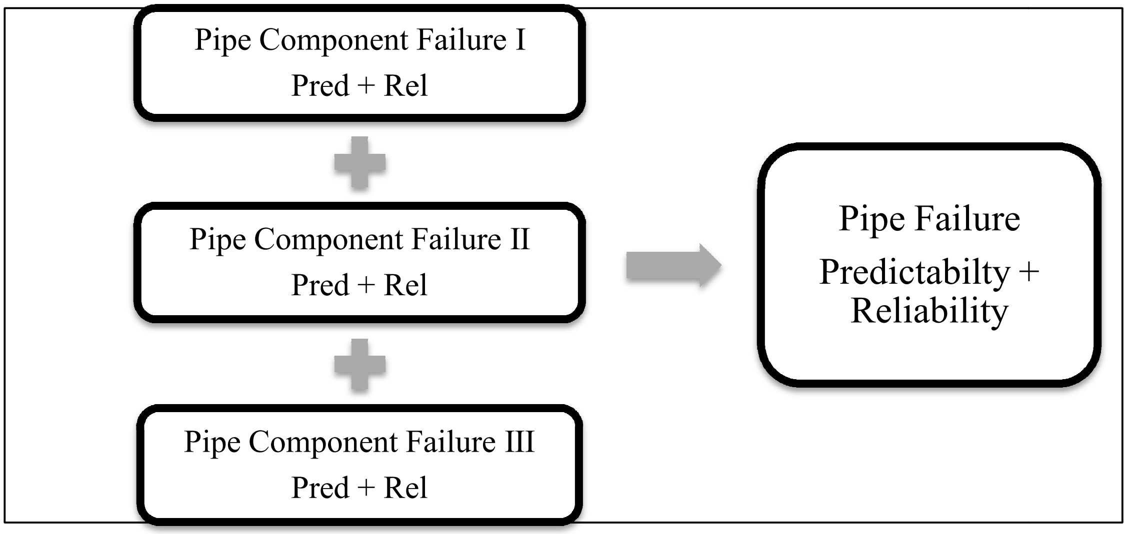

Figure 36: The relationship between pipe component failures and pipe failure.

Stage 6:

The final predictability index of the pipe is evaluated by considering the four dependant factors of the pipe as a structure, joint failure, high-risk scenarios/situations and water quality. Figure 37 illustrated the evaluation of the final predictability index.

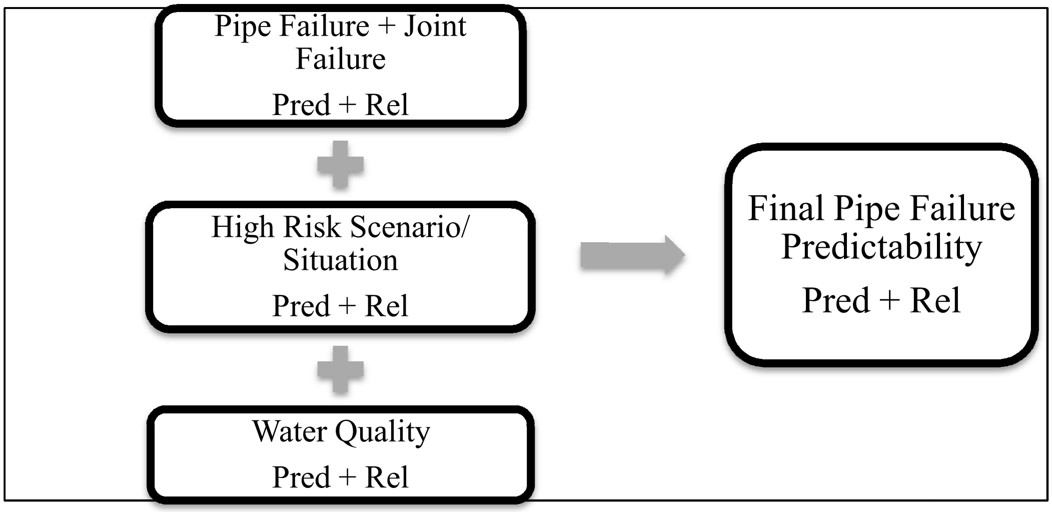

Figure 37: The relationship between pipe component failures and pipe failure

The final deliverables of the research would be a model to calculate the predictability index with the knowledge/confidence of data parameters input in the model. In case of predictability, the data parameters influencing any water pipe system is close to 100 parameters. Since utilities do not have the financial capacity to collect all the parameters on a regular basis, the reliability of the predictability index thus calculated is in question. Hence, each parameter used for the evaluation of the predictability index is evaluated for its reliability. Therefore, the final predictability index has a reliability index included. The predictability and reliability index are on scale of 1 to 5 as shown in Table 8 and Table 9. The outcome of the Predictability Index and its Reliability Index are two indices of number range from 1 to 5. Rank “1” in predictability index refers to low predictability of failure of the pipe in the given condition/situation. A predictability rank of “5” refers to a higher predictability of failure. In case of reliability, rank “1” means least confidence in data values and “5” means highly reliable data/information.

Table 8: Range of Predictability

Predictability	**Predictability of Pipe Failure**
1	Very Low
2	Low
3	Moderate
4	High
5	Very High

Table 9: Range of Reliability

Reliability	**Confidence of the data**
1	Scarce Data/ No Data
2	Less Data/ Educated Guesses
3	Indirect Data
4	Reliable Data/ Incomplete Data
5	Highly Reliable Data/ Direct Data

Low predictability indicates lower risk on the pipe system. However, before reaching to this conclusion, one should consider the reliability index.

- Low predictability in combination with low reliability implies less knowledge with the utilities and hence the value of predictability index derived cannot be of much use to the utility.
- Low predictability index with high reliability index implies the utility has high confidence in the data they are collecting and the pipe is not in risk.

- High predictability index with low reliability indicates, though the utility is not collecting all the parameters, the parameters it is collecting are capable of identifying risk.
- High predictability index and high reliability index indicates that the pipe is in danger and the data collected is highly reliable.

CHAPTER 5. METHODOLOGY TO CALCULATE CONDITION ASSESSABILITY INDEX

Condition Assessability Index is a measure for the utility to evaluate their abilities to prevent the pipe failure. This is directly connected to the predictability index.

The data for evaluating the predictability index has to be collected through one of the following technologies/methodologies:

1. Manual Inspection: Inspection done by human based on checklists. The authenticity of the data hence collected through this methodology is questionable.
2. Laboratory Test: Laboratory tests are the tests where samples are collected from the site and tested in the laboratory.
3. Field Test: Field tests are the tests conducted on the site itself. These tests are of two types: internal assessment technologies and external assessment technologies. Internal assessment technologies are technologies which need interruption of the flow to inspection the pipe from the insides. External assessment technologies are technologies which do not need interruption of the flow as it is inspected from outer surface of the pipe.

The stages for evaluating the Condition Assessability index are described below in Figure 38. Since evaluation of Condition Assessability, keeping in mind the complete pipe structure would be complicated and not appropriate.

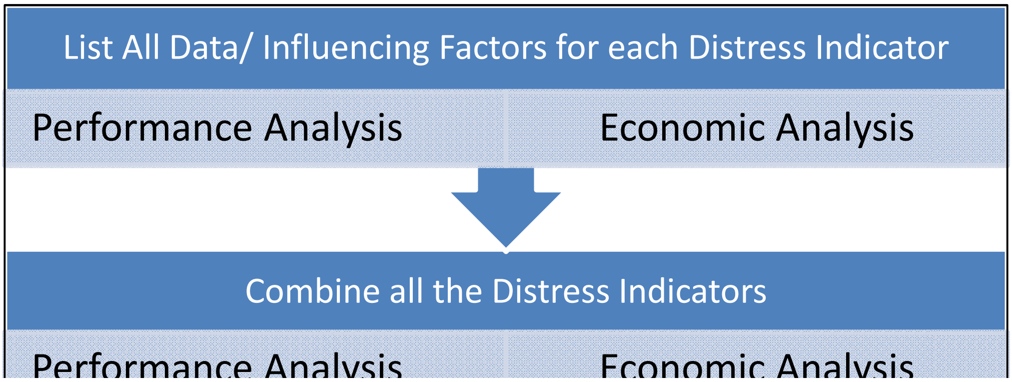

Figure 38: The two step evaluation of Condition Assessability

Pipe Components to Technologies Co-relation

The technologies are listed and identified according to the various diameter pipes they can be used for and the various distress indicators they can detect. Condition Assessability Index constitutes both the technologies which detect the distress indicators as well as the data parameters which explain the cause of the distress. This methodology is clearly explained with the help of Figure 39 and Figure 40.

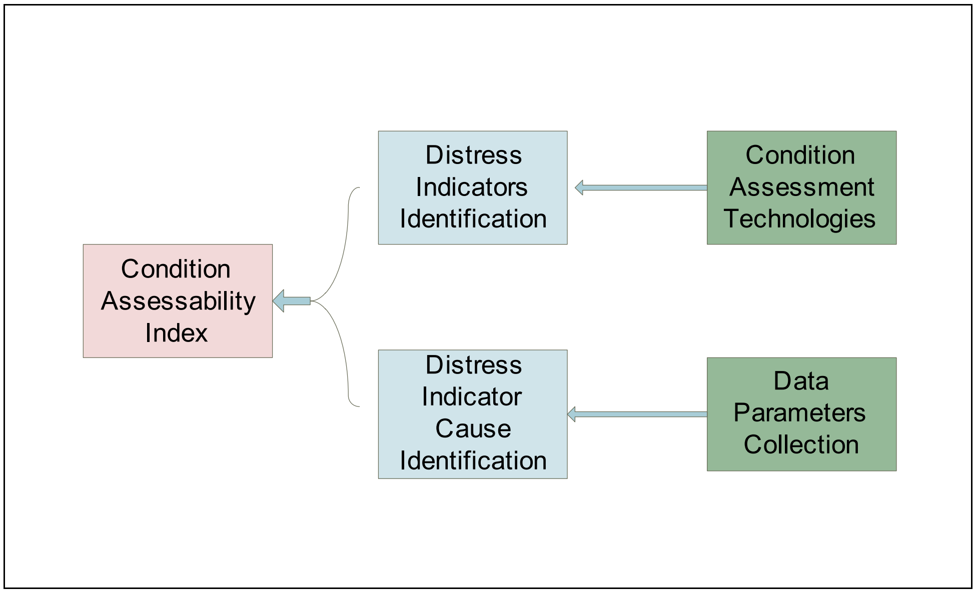

Figure 39: Method for calculation of Condition Assessability Index

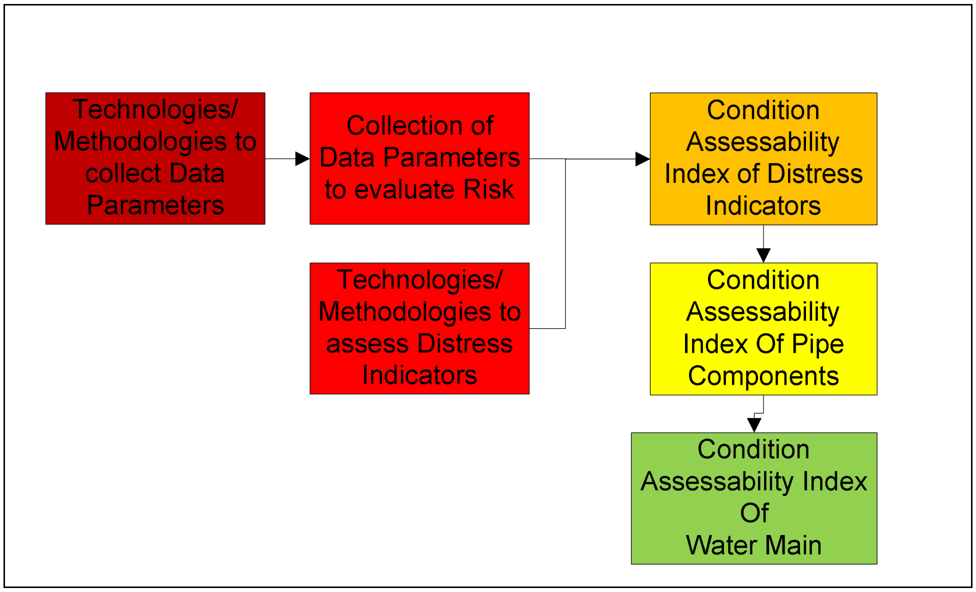

Figure 40: Flowchart of the methodology for the development of Condition Assessability Index

Evaluation 1: Performance Analysis

The performance analysis for the technology is done on the following basis:

1. Evaluation of data collected
2. Direct or Indirect Data
3. Rate of measurement
4. Data Validation
5. Utility of the data collected

Evaluation 2: Economic Analysis

The economic analysis for the technology is done on the following basis:

1. Cost per linear footage
2. Set up Charges
3. Direct and Indirect Charges

Predictability Index helps utilities evaluate the high-risk the pipe is prone to (it could be a pipe component or high-risk situation/scenario). The Condition Assessability Index is calculated after some evaluation and charts are prepared for condition assessability of each high-risk and a general case of low and very-low risk pipes. Once the Predictability Index is calculated, it would direct the utility towards which Condition Assessability Index Charts to be referred to know what condition assessment technologies/methodologies could be used on the pipe system to continue monitoring the system more efficiently.

The final deliverables of the predictability index is obtained from the knowledge of data parameters input in the model. In case of Condition Assessability, the distress indicators possible and the technologies that can detect these distress indicators are the required input. Since the knowledge of the distress indicators and the technologies are independent of the pipe system, the condition assessability index thus calculated is a representative for a particular type of pipe. As the knowledge of the pipe system or technologies increases, the indices may be re-evaluated. The performance analysis and economic analysis are on scale of 1 to 5. Table 10 and Table 11 explain the scale of the performance analysis and economic analysis.

Table 10: Range of Performance Analysis

Performance Analysis	
1	Poor efficiency
2	Bad efficiency
3	Moderate efficiency
4	Good efficiency
5	High efficiency

Table 11: Range of Economic Analysis

Economic Analysis	
1	Poor efficiency
2	Bad efficiency
3	Moderate efficiency
4	Good efficiency
5	High efficiency

CHAPTER 6 DETAILED METHODOLOGY TO CALCULATE PREDICTABILITY INDEX FOR PCCP WATER MAINS

System Description

The pipe system has been analyzed to list the various data parameters that influence the performance of the system. In case of PCCP, the factors are close to 80 parameters and are listed in Appendix F. The influencing factors have been categorized according to the stage of the pipe lifecycle. The various stages of the pipe lifecycle are Manufacturing, Installation, Operations & Maintenance, Repair, and Rehabilitation.

Understanding Pipe Failure Modes and Mechanisms

PCCP pipes are of two types: Embedded Cylinder Pipe (ECP) and Lined Cylinder Pipe (LCP). PCCP pipe with diameter of 48" and more are of the embedded cylinder pipe. PCCP pipe with diameters up to 48" and including 48" are of the lined cylinder pipe. AWWA 304-92 describes the various design specifications, requirements, etc. for PCCP pipelines. Figure 41 illustrated a brief classification of PCCP.

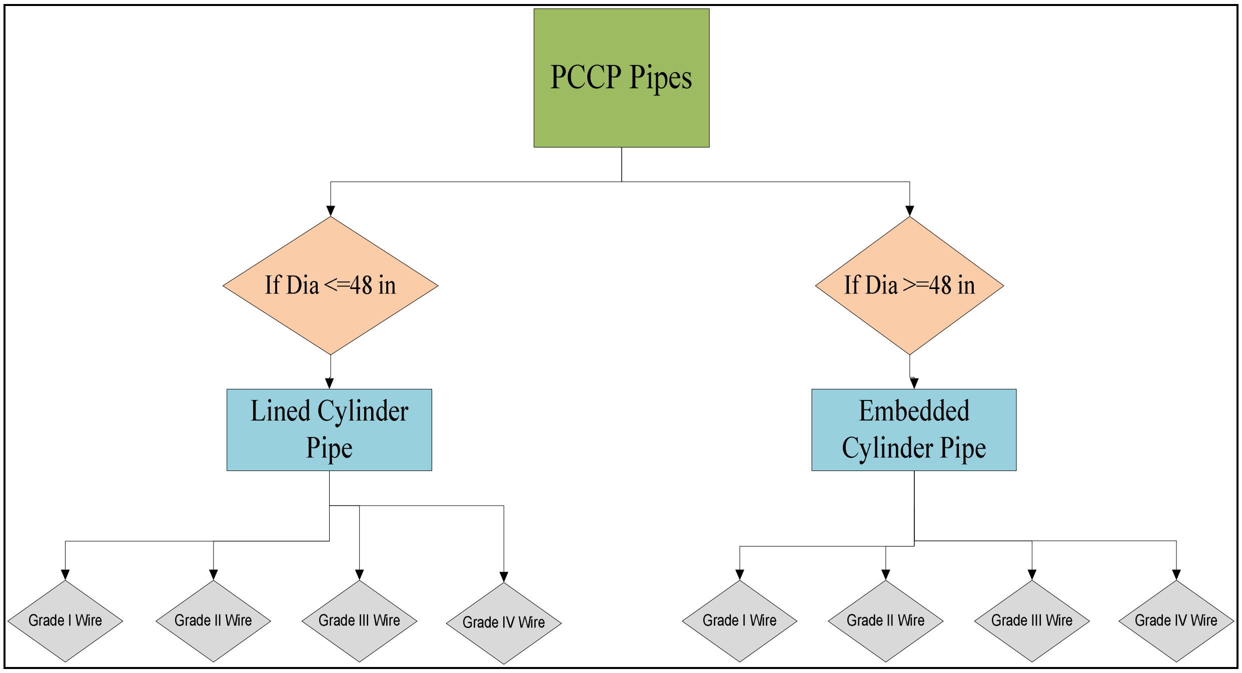

Figure 41: Classification of PCCP Pipes

The various components of the PCCP pipe are Mortar Coating, Pre-stressed wire, Steel Cylinder, and Concrete Core. Embedded Cylinder Pipe Components are illustrated in Figure 42; Lined Cylinder Pipe Components are illustrated in Figure 43. In Embedded Cylinder Pipes, the steel cylinder is a part of the concrete core and hence the name embedded cylinder pipe.

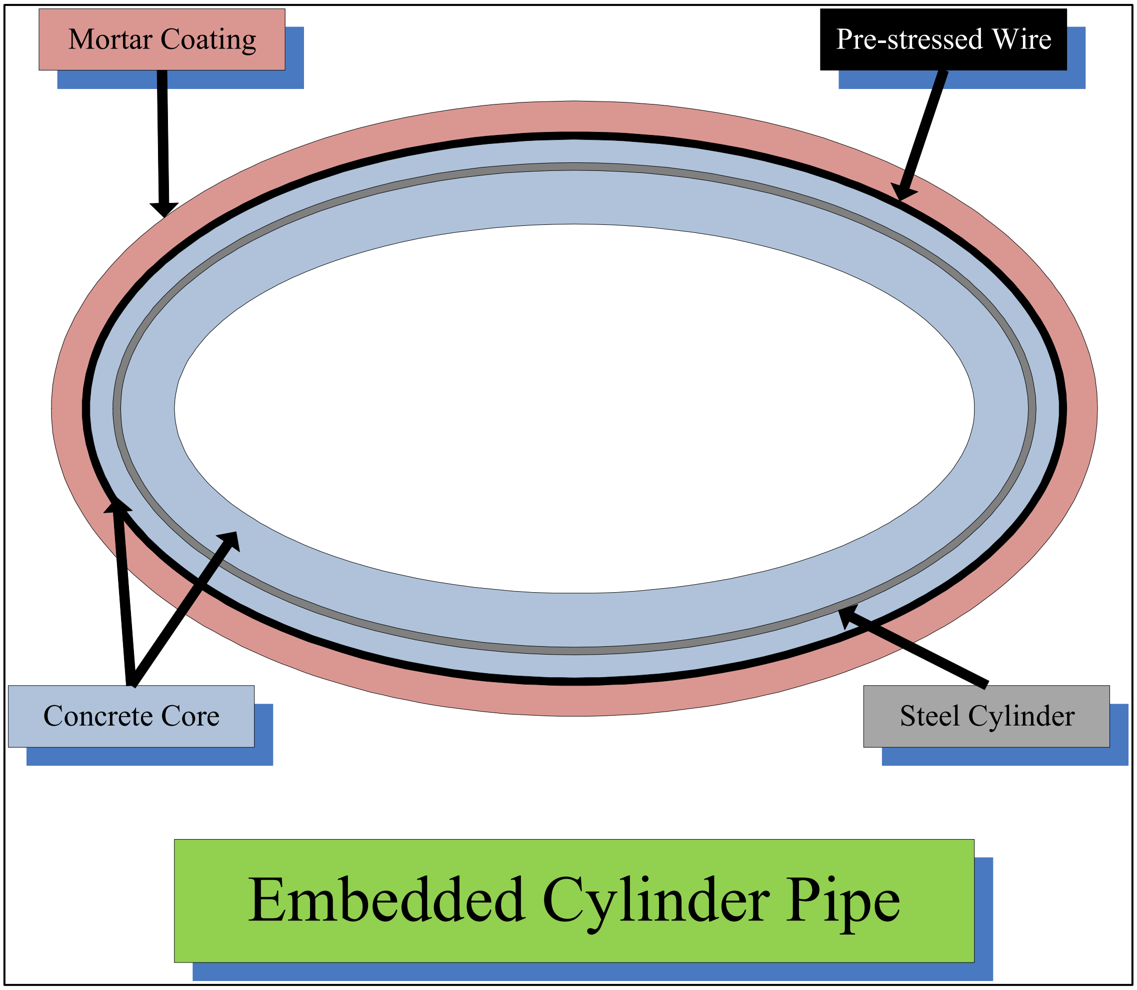

Figure 42: Schematic of Embedded Cylinder PCCP

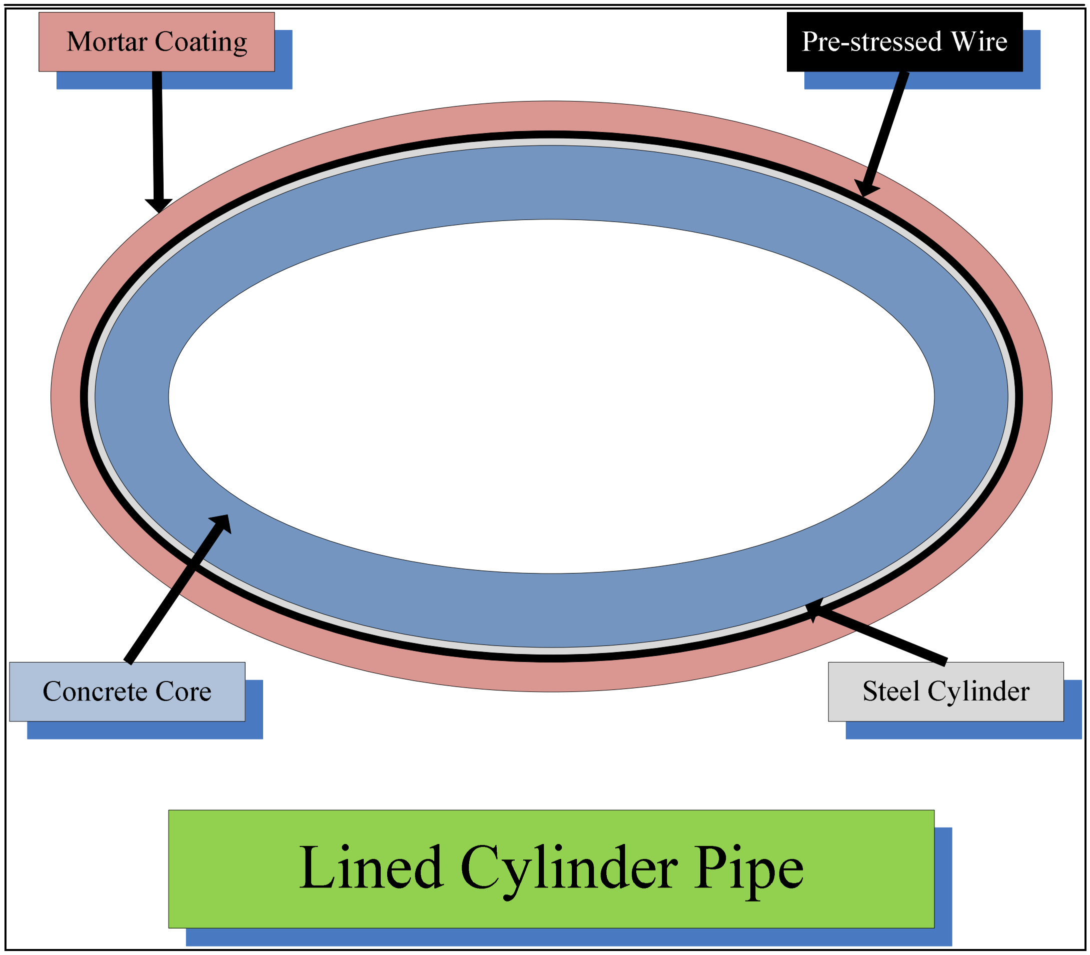

Figure 43: Schematic of Lined Cylinder PCCP

The Various types of Distress Indicators/Failure modes

The various types of distress indicators are listed below categorized by the pipe structure they influence. The various pipe components are interior mortar coating, exterior mortar coating, pre-stressed wires, concrete core, steel cylinder and joints. The list of distress indicators along with their pictorial library is included in this section.

PCCP Interior Mortar

The interior mortar can fail due to various reasons. The reasons can be poor manufacturing, pressure variations, high surge pressure, contaminations, etc. the various distress indicators in interior mortar coating are spalling, crack, coloration and corrosion.

PCCP Exterior Mortar

Exterior mortar is very similar to the interior mortar structurally but the factors, which influence its failure, are very different. The exterior mortar fails for various reasons like corrosive soils, water table in the soil, loading on the pipe system, poor manufacturing, poor installation, etc. The various distress indicators of exterior mortar coating are spalling, crack and corrosion.

PCCP Steel Cylinder

For the steel cylinder to fail, the core should either fail or crack to let the steel cylinder fail. Alternatively, the steel cylinder was not manufactured or welded properly. The various distress indicators of the steel cylinder are corrosion, pin hole and crack.

PCCP Pre-stressed Wire

The pre-stressed wires are the main components of the PCCP. The wires can break due to manufacturing defect, loss of protective layer around them due to corrosion or failed mortar or concrete, etc. The various distress indicators of pre-stressed wires are loss of protective layer, corrosion, corrosion and wire break.

PCCP Concrete Core

The concrete core fails for various reasons. For example, cracks on the concrete, corrosion of concrete, etc. The various distress indicators are crack, delamination and corrosion.

PCCP Joint

PCCP joints can fail due to misfit of joints, installation errors, corrosive soils, etc. The distress indicators for joints are change in alignment, joint displacement, joint diaper failure, joint leaks and joint corrosion.

Deformed pipe, leaks, and pipe burst are other indispensable failures faced by any pipeline. Pipe burst or the final pipe failure can be a result of one of the earlier mentioned failure modes or a combination of some.

WSSC Findings on Possible Causes of PCCP Failure

WSSC has conducted various studies, both theoretical and experimental, to understand the behavior of the PCCP pipes. Their observations have been documented and listed in this section.

Steel Cylinder

Barlow's Formula - an equation is used to calculate the relationship of internal pressure to allowable stress, nominal thickness and diameter of pipe. This formula gives the burst pressure for just the steel cylinder. This means that even if the wire has a few broken turns the pipe will tolerate a water pressure much greater than this until approx 40 wire turns are broken at end of the pipe length, any additional loading on the cylinder caused by pipe weight by position on hill with a missing diaper will lower this pressure.

At what water pressure will the steel cylinder of the 48 inch PCCP pipe "alone" burst?
$P= (2*S*t)/D$ - Barlow's equation
P- Internal pressure (psig)
S- Unit Stress (psi) [yield strength]
t- Nominal wall thickness, inch
D- Outside diameter of cylinder, inch

Pre-stressed Wire

WSSC through their experience have observed that it takes approximately 40 turns to break at the end of a pipe or near 100 wire turns in the centre of the pipe for the pipe to fail. If these conditions are being approached it is more than likely they can be identifies inside the pipe by one or more of the following inspection methods: Visual, Seismic Pulse Echo NDT and/ or

Electromagnetic inspection. The classes of the wire affect how and when PCCP pipes fail. For the pipe failure to occur you must have one or more of the following conditions as initiation step:

Class I and Class II wires: Pipes and pipeline services with these classes of wires have very good service histories.

1. Damage during installation usually at bell or spigot end, or rocks in bottom of trench,
2. Poor welds in cylinder or at end rings. (leaks water to cylinder and wire)
3. Pinched/ Leaked Gaskets
4. No diaper at joint or incomplete
5. Poor taps or corroding saddles
6. Over pressuring the pipeline causing cracks to form in the mortar
7. Soils ground waters high in carbon dioxide

Class III can be like I and II above however there is a very high likelihood that some pipes in the pipeline have been made with a batch of this high strength wire that is very sensitive to hydrogen embrittlement, some lengths of wire on a pipe can also be very sensitive to hydrogen embrittlement. If the wire is sensitive to hydrogen embrittlement it could have started to break before it left the factory. Once wires break the mortar delaminates, cracks form, and corrosion process starts off as soon as ground water reaches the wires. Some pipes in a class III wire specified pipeline must always be considered at risk. Pipeline risk in this case is above average.

Class IV

Before the causes listed for Class I and II occur, this wire is extremely sensitive to hydrogen embrittlement and pipe and the wires can break any time. Once wires break, the mortar cracks and allows the ground water in and the cylinder strength can no longer sustain the hoop stress. These pipelines are at very high risk of failure.

Chemical Attacks

Carbon-dioxide present in the soil and groundwater can corrode or eat up the concrete. The thickness of concrete as seen in the case study can change by vast portions. The $Ca(OH)_2$ in concrete reacts to form $CaCO_3$. The CO_3^{2-} is found in various forms on the concrete to verify the action of the carbon-dioxide.

The source of the CO_2 is not clear. But the air could be the main source of CO_2 to the ground. The other probable source of CO_2 in this region could be residues of volcanic activity.

SO_4^{2-} : In regions around the region in consideration the problem faced to more due to sulphates rather than carbonates. Rains and water flow have resulted in heavy destruction due to the presence of sulphates.

Cl: Chloride from treated water can react with the steel cylinder from the inside of the pipe to form $FeCl_3$ (Ferric Chloride). One Ferric chloride is formed the corrosion is accelerated. Hence, the corrosion started with Cl in water is more accelerated than other corrosion.

Cathodic Protection

The presence of oil pipelines with cathodic protection nearby can lead to hydrogen embrittlement of the wires leading to wire breaks. In past, some PCCP had been "protected" with Cathodic protection leading to vast failures. Of the various Cathodic protections, Zinc works out to be harmless on PCCP wires. However, this is not a recommended practice to be followed on the pipeline.

Failure Causes Identified

AWWARF has identified various causes for failure of PCCP pipe based on design, manufacturing, installation, and other influencing factors, as shown in Table 12.

Table 12: List of failure causes in PCCP pipes

a	Rupture or Break- Broken wires	d	Cantilever (bending)
m+i	Leaking at joints	i	settlement
m	Cracks in core	d	surge
m	Dented cylinder	i	Looped gasket
m	Low quality of wires	i	Poor bedding
m	Low quality of mortar- density/ thickness	i	Wrong pipe class
d	High chlorides in soil-corrosive/aggressive	m	Low quality of core
d	Inadequate joint restraint	m	Cracks in joint welds
i	Construction Damage	m	Wire spliced and re-stressed
m	Cracks in cylinder welds	m	Over wrapping
m	Coating delamination	d	Hydro Test
a	Hydrogen embrittlement	i	Poor Field Weld
m	Inadequate pre-stress	d	Excess External Load
i	Missing joint coating		CO_2 in soils

Where, a=all; m= manufacturer defect; i= installation; d= design;

Various failure paths have been identified and charts have been made. An example of a failure path is illustrated in Figure 44. All recorded failures have been understood to form various failure paths for the failure of PCCP pipelines. This has been explained further in the following section.

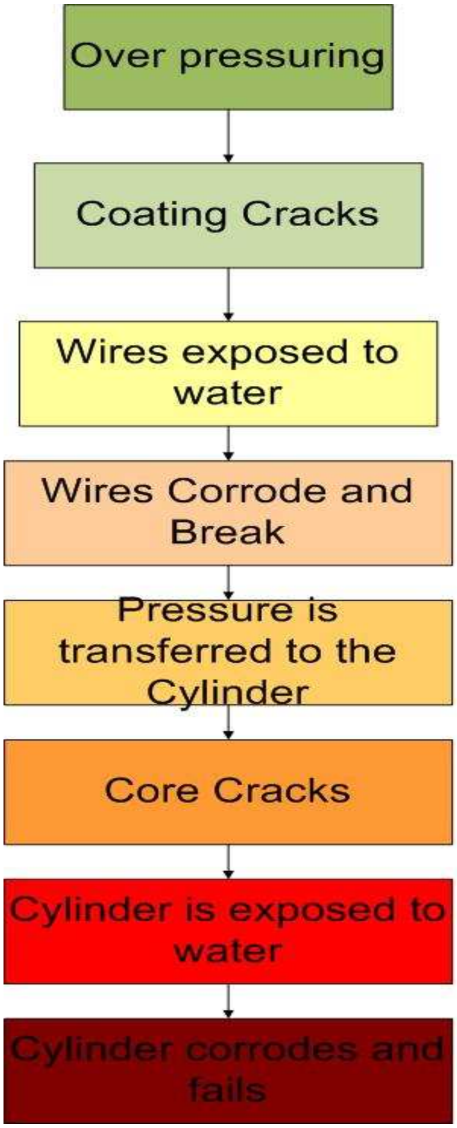

Figure 44: Possible Failure Path

PCCP Failure Mechanisms

The failure mechanisms are studied by sub-classifying the PCCP pipe depending on the diameter, the pipe structure and the wire type. This classification is illustrated in Figure 45. Further, Figure 46 explains which distress indicators are most likely to occur in the particular pipe in consideration. Figure 47 shows the summary of the failure mode and mechanisms possible in PCCP and the probable causes for the same.

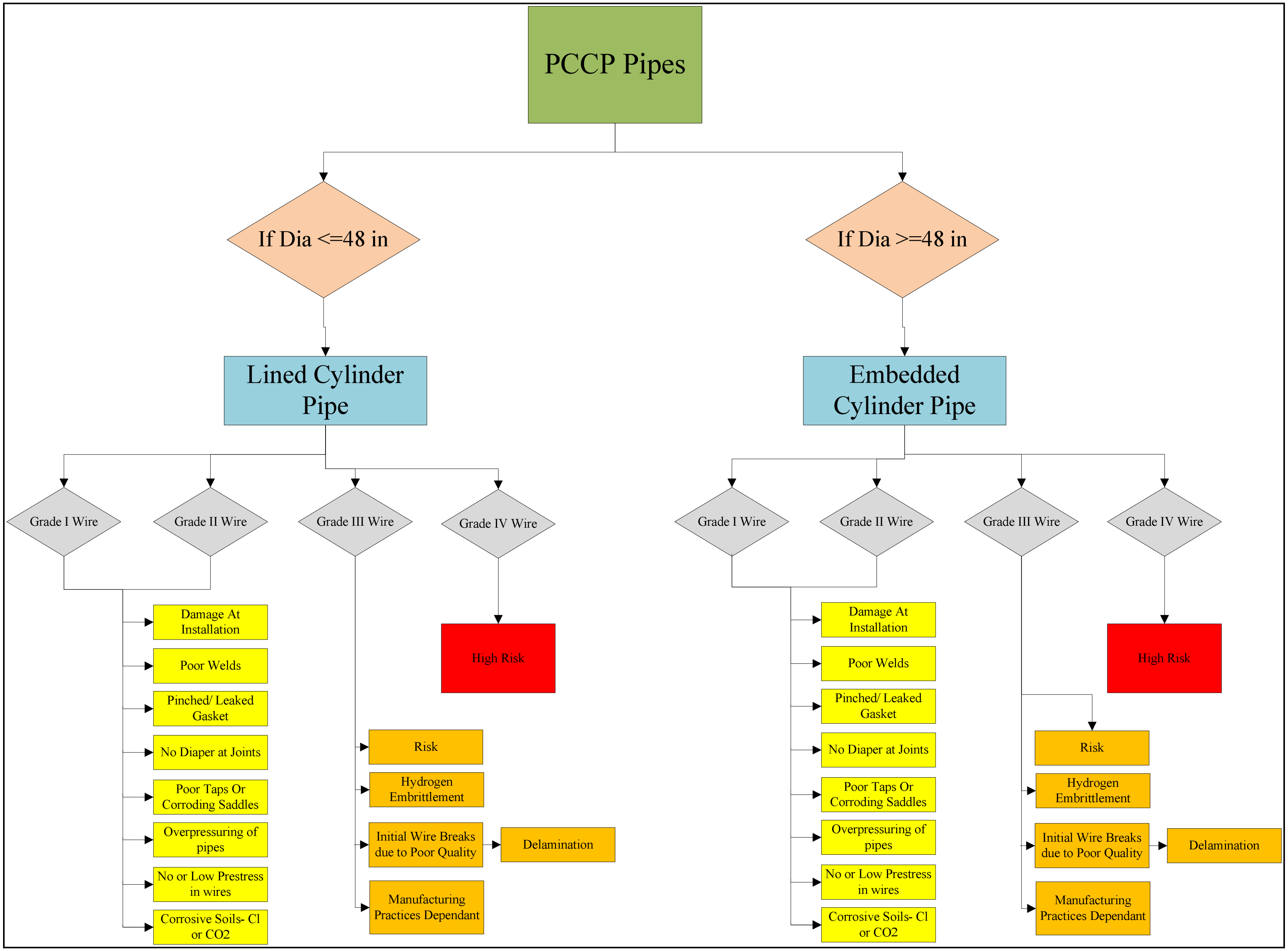

Figure 45: Classification of PCCP pipes and Likely Risks

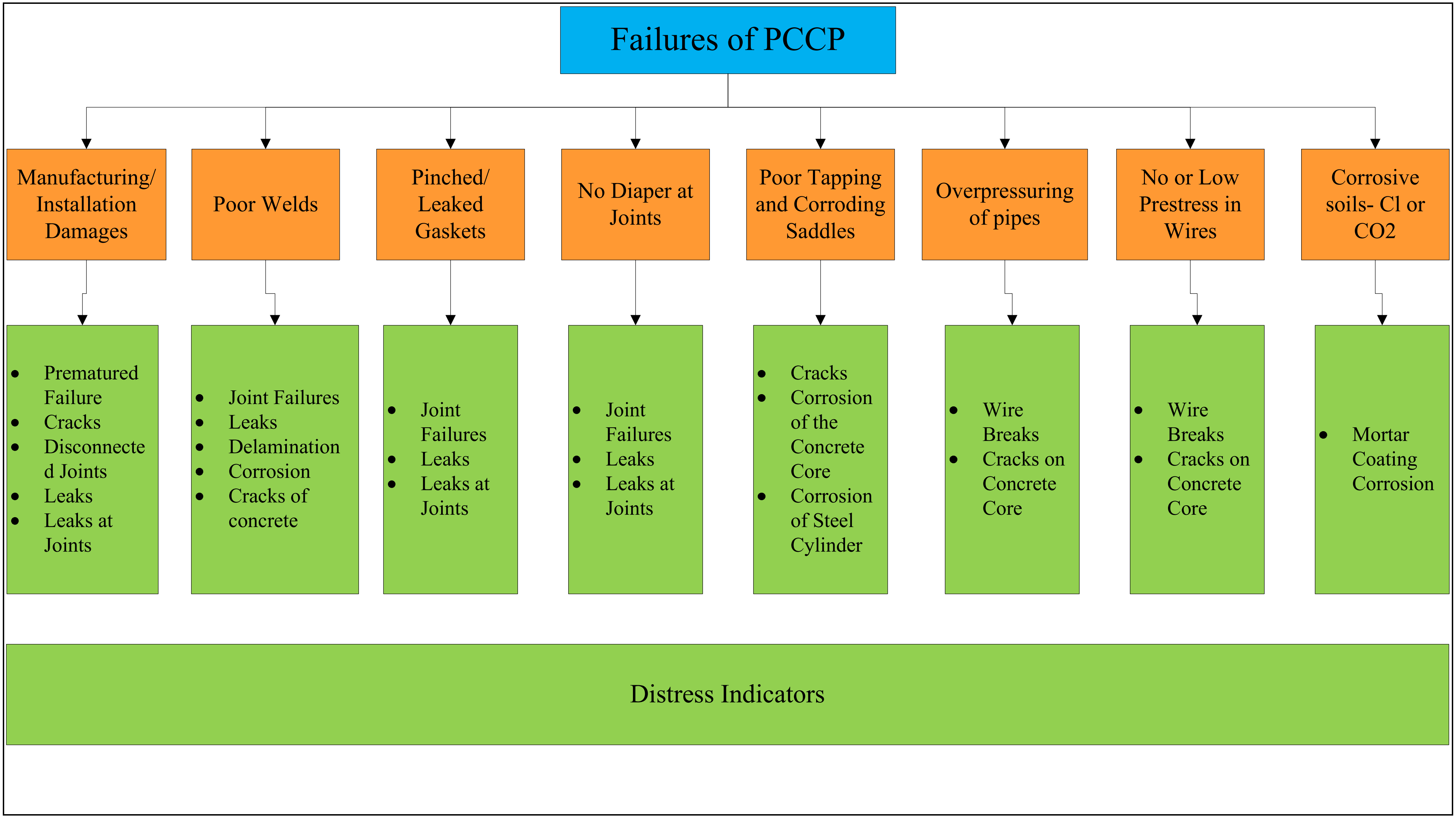

Figure 46: Distress Indicators possible from the risk exposed

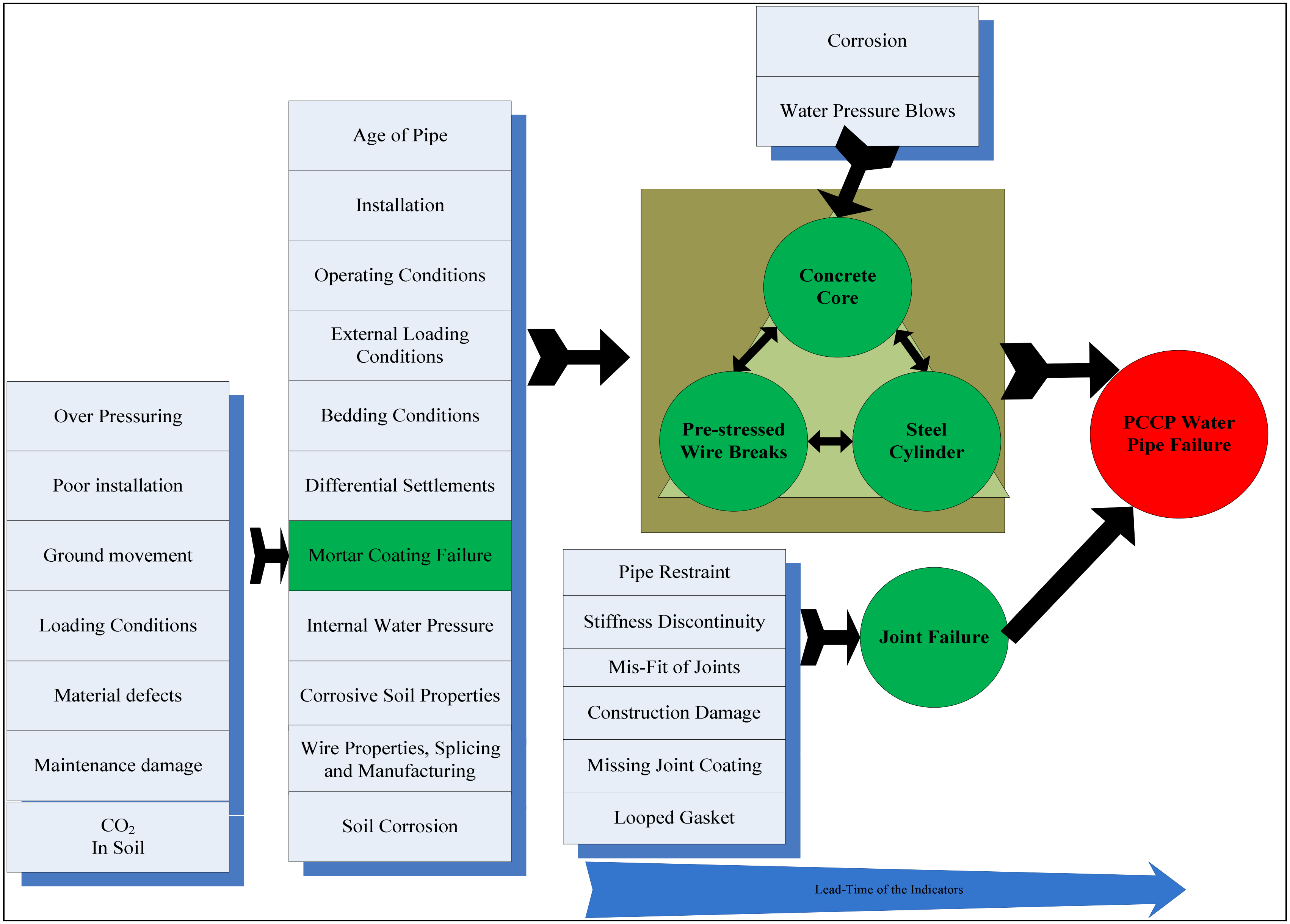

Figure 47: Failure Modes and Mechanisms of the PCCP Pipes

Development of Predictability Index

Stage 1: Severity, Occurrence and Reliability of Data/ Influencing Factors

The Severity/Occurrence and Reliability of the various influencing factors is evaluated from the data input and source of the data input. ***This calculation is done automatically in Microsoft Excel Spreadsheet***. An example for evaluation of predictability index is explained in this section. The data parameters input for this calculation are in appendix F. Table 13 shows a part of such calculation which shows the calculation of severity, occurrence and reliability of data/ influencing factors where as the complete calculation is included in appendix F.

Table 13: The evaluation of Severity/ Occurrence and Reliability of Influencing factors

						This is where the data is to be included by the users	**Here the Users have to justify their data by specifying their level on confidence on the data**		
No	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
		The stage of the pipe's life where the required data is to be collected	**Explanation of the inputs that are required**				Direct Data- 5, Incomplete Data-4, Indirect Data-3, Educated Guess-2, No Data-1	Very High-5, High- 4, Medium-3, Low- 2, Very Low- 1	Very High-5, High- 4, Medium-3, Low- 2, Very Low- 1
1	Lining thickness/ design thickness	Manufacturing, Installation, Operations	The ratio of the present lining thickness to the design lining thickness	Ratio	0 onwards (Ideally 1)	0.5	4	5	4
2	Manufacturing Inspection	Manufacturing	Manufacturing Inspection is inspection for cracks in pipes before the pipes are sent for installation	Level	inspected and no cracks-2, inspected and minor cracks-1, inspected and major cracks-0, not inspected-1	1	4	3	4
3	Curing Time/ Design Curing time	Manufacturing	the ratio of the curing time provided for the concrete against the design concrete curing time	Ratio	0 onwards (Ideally 1)	0.5	3	5	3

Sample Calculations:

Line Thickness:

The range for the line thickness is from 0 onwards and ideally 1. Since our input here is 1, which is the ideal condition required. The output of severity and occurrence is also 1 which means "very low" severity/ occurrence of failure through the contribution of this factor. The range for the calculations of severity/ occurrence from the given line thickness ratio is listed in Table 14.

Line thickness:

Table 14. Severity/ Occurrence Calculations of Line Thickness from input data

Measured/ Actual (lt)	Severity/ Occurrence
<0.6	5
0.6< = lt <0.75	4
0.75 < = lt <0.9	3
0.9 < = lt < 1	2
1	1
1< lt < = 1.1	2
1.1 < lt <= 1.25	3
1.25 < lt <= 1.4	4
lt> 1.4	5

Manufacturing Inspection:

The range for the manufacturing inspection is divided in 3 levels. The levels are inspected and no cracks (2), inspected and minor cracks (1), inspected and major cracks (0) and not inspected (1). The risk is calculated accordingly. With inspected and no cracks the Severity/ occurrence is 1. With inspected and minor cracks or no inspection the severity/ occurrence is 3. The severity/ occurrence is 5 for inspected and major cracks as the input.

Curing time/ Design Curing Time:

The range for the ratio of the curing time to the design curing time is from 0 onwards with an ideal value of 1. The range of curing time ratio to the severity/ occurrence is the same as that of lining thickness. Therefore the result range is also the same. If the curing time is close to 1 then the lower risk. In this case since curing time is only half the design curing time the risk is really high.

Reliability of Data:

Reliability of data is directly dependant on the kind of input on the data.

Stage 2: Possible Failure Paths

All the failure paths are listed and the weights have been evaluated. This is described in Table 15. Appendix G has the complete evaluation of the predictability and reliability of the failure paths for the given example.

Table 15: Evaluation of Predictability and Reliability for the Various Failure Paths

S.No.	Failure Path	Influencing Factors	Severity/ Occurrence	Reliability
1	Impact load on rigid surface-mortar cracking		5	4
		Load(dead load +live load)/ Design Load	5	4
		Loading Condition (Dead Load)	5	4
		Loading Condition (Live Load)	3	1
2	Poor Constructability of the design=> poor construction practices=>cracked lining and coating		2	2
		Design Constructability	3	1
		Installation Inspection/ Orderly Installation	1	3

Sample Calculations

Failure path 1: Impact load on rigid surface- mortar cracking

The weights included for this are loading conditions both dead load + live load. In this particular case, the value of severity/ occurrence for load/ design load is 5 and reliability for this is 4. Since this is a prominent number, it reflects on the severity/ occurrence and reliability of the particular failure path. Else, the index would be a weighted average.

Stage 3: Distress Indicators

The weights have been hard-coded in the Microsoft Excel Spreadsheet to provide the final distress indicator. The various distress indicators are shown in the Table 16. Appendix H has the complete evaluation of Predictability and Reliability of the Various Distress indicators for the given example.

Table 16: Evaluation of Predictability and Reliability of Distress Indicators along with the influencing weights

S.No.	Distress Indicator	Failure Path	Severity/ Occurrence	Reliability
		Interior Mortar Coating		
	Spalling		3	3
		Hydrotest Pressures> Design pressures/Design Surge Pressure-Coating Cracks	1	5
		Variation of the PCCP cores=> Cracks	3	1
		Inadequate pipe restraint- mechanically restrained joints- opened of mortared joints- steel joint ring exposed to corrosion- steel joint ring corroded- steel joint expands and cracks the coating-exposes the wire	3	2
	Crack		2	4
		Hydrotest Pressures> Design pressures/Design Surge Pressure-Coating Cracks	1	5
		Inadequate pipe restraint- mechanically restrained joints- opened of mortared joints- steel joint ring exposed to corrosion- steel joint ring corroded- steel joint expands and cracks the coating-exposes the wire	3	2
		Inadequate or improper curing prior to prestressing => Coating shrinkage=> exposure of wire reinforcement=> corrosion	2	3
		Too Many fine aggregates=> Coating shrinkage=> exposure of wire reinforcement=> corrosion	1	5

Stage 4: Pipe Structures Failure Predictability

The evaluation of the predictability and reliability of the various pipe components for the given example are shown in Table 17.

Table 17: The Predictability and Reliability for the various pipe components

S.No.	Pipe Component	Distress Indicator	Predictability	Reliability
	Interior Mortar Coating		1	5
	Spalling		1	5
	Crack		1	5
	Coloration		1	4
	Corrosion		2	4
	Exterior Mortar Coating		5	3
	Spalling		5	3
	Crack		1	4
	Corrosion		2	3

Stage 5: Pipe Failure Predictability

The predictability index of the pipe burst is evaluated by the similar logic used for evaluation of the failure mode. The failures of mortar coating, pre-stressed wire, concrete core, joints, pipe shape and leaks. Figure 48 shows the final contributing failures towards the predictability index.

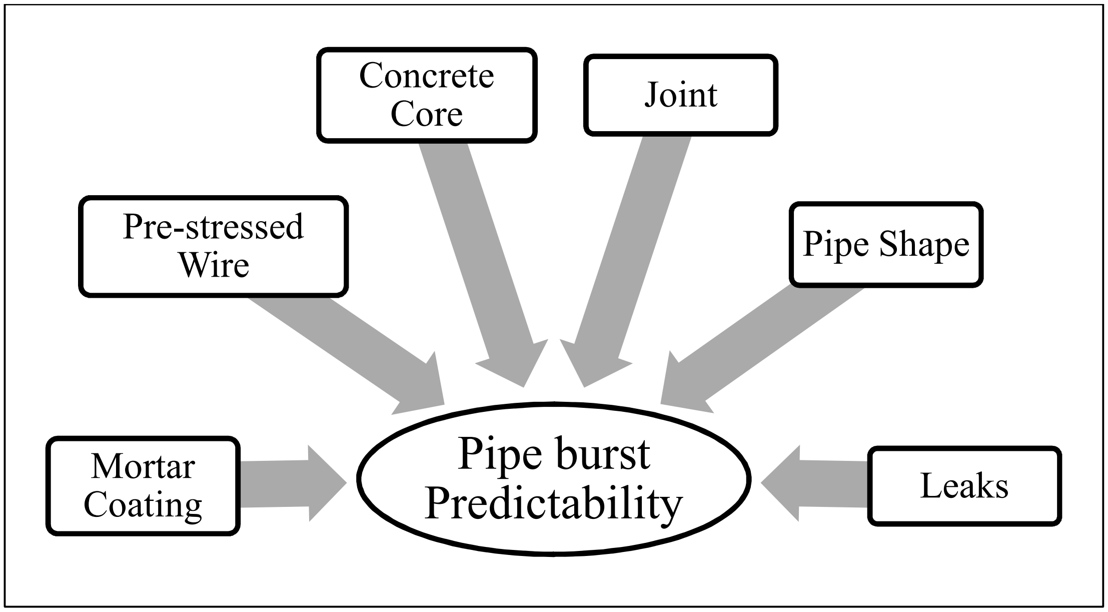

Figure 48: Contributing Factors for the evaluation of the Predictability Index

The final evaluated Predictability index for the PCCP pipes with the given example is shown in Table 18.

Table 18: The Final Predictability and Reliability evaluated

	Pipe Components	Predictability	Reliability
Pipe Structure Predictability		5	3
	Interior Mortar Coating	1	5
	Exterior Mortar Coating	5	3
	Steel Cylinder	2	4
	Pre-stressed Wire	4	4
	Concrete Core	5	3
	Joints	3	5
	Deformed Pipe	1	4
	Leaks	1	4

Stage 6: Final Predictability Index

The Evaluation of the Predictability Index can be summarized as shown in Figure 49.

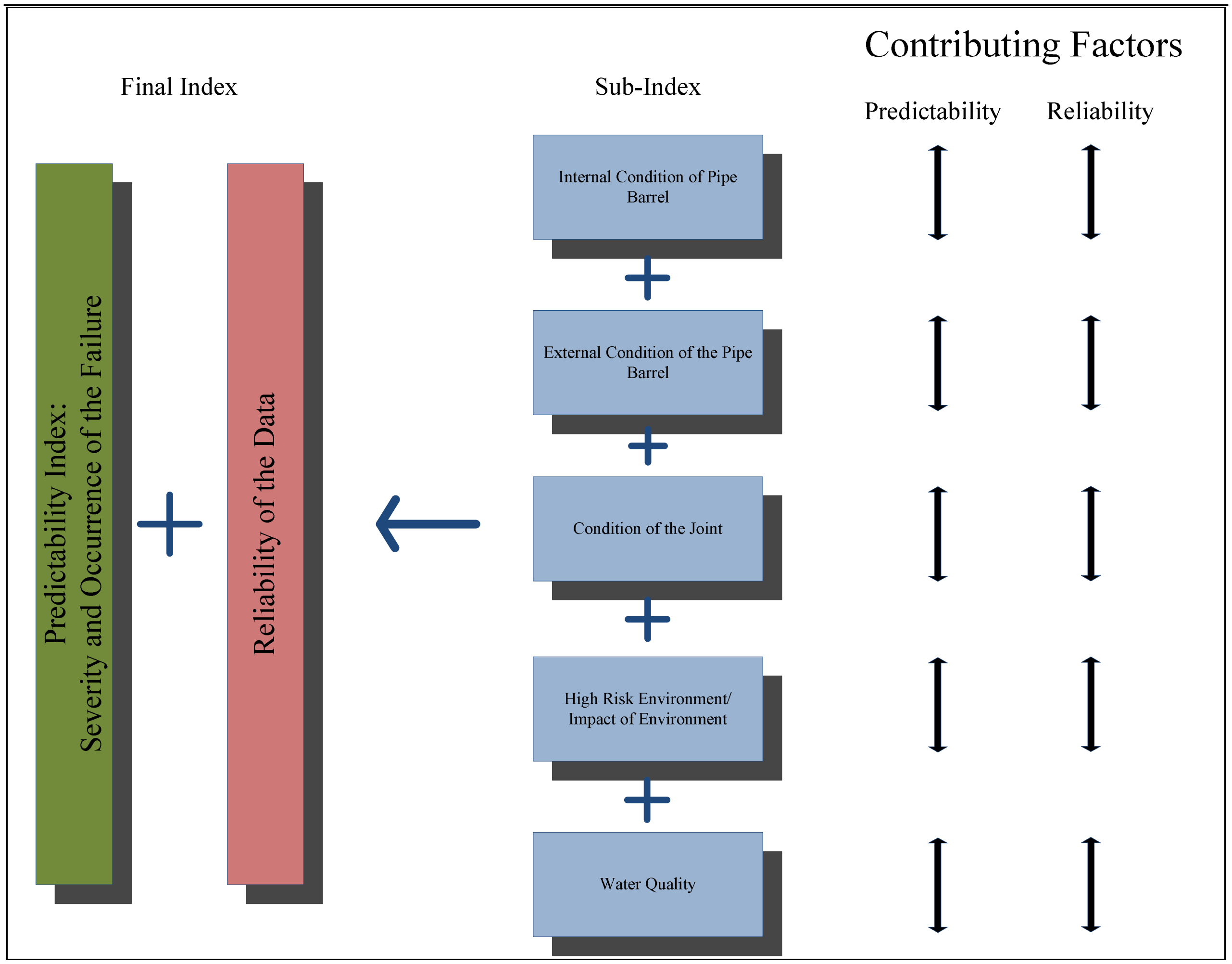

Figure 49: Calculation of Predictability Index

The Predictability Index of PCCP Pipe is included in the appendix, as shown in Table 19.

Table 19: List of Appendix for Predictability Index

	Appendix
ECP Predictability	I
LCP Predictability	J

The Data Parameters

The data required for complete evaluation of PCCP pipe system are approx. 88 parameters. However, it may very laborious for the utility to fill in 88 parameters to evaluate the predictability index. So there is a two-step process to evaluate predictability index. The selected parameters presently consist of 60 parameters. If initial evaluation indicates high-risk, the utility can proceed to evaluate the index using the complete list of data parameters. Appendix K contains the predictability index with the selected parameters.

The present selected parameter predictability index contains 60 parameters, which is still on the higher end of parameters required for evaluation. Each utility's requirements for the selected parameters may change based on their data collection methodology and associated risk.

Proposed Three Level Approach for Calculating PCCP Pipe Failure Predictability

The level of detail taken into account during the calculation of the Predictability index is very high. The predictability index includes 88 parameters which are 71 data parameters, 9 high risk situations/ scenarios, and 8 water quality parameters. It would be very difficult for the utility to collect all 71 data parameters apart for the other 17 parameter. The 17 parameters of the high risk situation/scenario and water quality are easy to collect and are mostly available with the utility. Therefore these parameters remain constant through the various levels of calculation of predictability index. So the predictability index has been modified to three levels considering the data parameters alone. The levels are described below.

Level 1 (critical parameters) – 38 parameters

Level 1 of the Predictability index is for small utilities that can collect limited data. 21 data parameters, 9 high-risk situations/scenarios and 8 water quality parameters constitute the level 1 predictability parameters. The level 1 predictability index contains only critical parameters. Since the number of parameters are reduced, the reliability of the index is automatically reduced. This level is advantageous for small utilities that do not have the resources to collect complete data. But the disadvantage of level 1 predictability index is that it reduces the reliability. The reduced 21 data parameters are included in Appendix U.

Level 2 (essential parameters) – 60 parameters

Level 2 of the predictability index is a calculation of the predictability index with 43 data parameters. 43 data parameters, 9 high-risk situations/scenarios and 8 water quality parameters constitute the level 2 predictability parameters. It encompasses the importance parameters for the calculation of the predictability index taking into consideration all the failure modes. However, this is not the exhaustive list of parameters and hence overlooks some important data and thereby reducing the reliability on the index. The predictability index calculation with 60 parameters is shown in appendix K.

Level 3 (preferable parameters) – approx. 88 parameters

Level 3 of the predictability index is the exhaustive list of data parameters. 71 data parameters, 9 high-risk situations/scenarios and 8 water quality parameters constitute the level 3 predictability parameters. The data parameters, failure modes, failure paths have been collected as a result of intensive literature review and WSSC case study. This is the preferable list of parameters for the calculation of predictability index. However, the disadvantage of this level of predictability index is that collecting the complete data would be very difficult.

CHAPTER 7. DETAILED METHODOLOGY TO CALCULATE CONDITION ASSESSABILITY INDEX FOR PCCP WATER MAINS

Condition Assessability Index is a measure for the utility to evaluate their abilities to prevent the pipe failure. Condition Assessability index considers and evaluates all the state-of-the-art technologies and methodologies to provide guidelines for the utilities towards what preventive measures need to be taken. This is directly connected to the predictability index. After the predictability index is calculated, it indicates the probable failure modes the pipe is prone to. The condition assessability index will then suggest the utility the technologies and/or methodologies to continue monitoring that pipe as per the failure mode it is prone to. This way the condition assesssability index will help the utility focus on the failure mode it is likely to face.

Development of Condition Assessability Index

Condition Assessability index is calculated for each pipe component taking into account their distress indicators. Condition Assessability index calculation takes into account two kinds of data collection. One way is by considering the technologies/ methodologies present to detect/ identify the distress indicators.

Another way is by tracking backwards the data parameters that indicate the high-risk associated with the pipe component. And the technologies/ methodologies that are used for collecting the data parameters are evaluated for their cost effectiveness and feasibility.

The data for evaluating the predictability index has to be collected through one of the following technologies/methodologies: Manual Inspection, Laboratory Test, and Field Test.

Technologies

Technologies are classified into four types: External Condition Assessment Technologies, Internal Condition Assessment Technologies, Emerging Technologies and Other Methodologies. The technologies specific to PCCP pipelines are listed in Table 20.

Table 20: The list of technologies that can be used for Pre-stressed Concrete Cylinder Pipe (PCCP) are:

S.No	Technology	Type of Technology	Assessment Parameter	Diameter
1	half-cell measurement	ETC	Corrosion	Any
2	Inductive Profiling	ETC	Leaks	Any
3	eddy current inspection	ETC, ITC	Wall loss and other pipeline defects	Any
4	infrared and thermography	ETC	Leaks	Any
5	Magic Carpet	ETC	Leaks	Any
6	visual inspection and sounding	ITC	Leaks, Wire breaks	Large Diameters
7	Leak Noise Correlators	ITC	Leaks	Any
8	acoustic leak detection	ITC	Leaks	>12 inch
9	acoustic emission monitoring	ITC	Wire Breaks	>=24 inch
10	Acoustic Loggers	ITC	Leaks	Any
11	Sahara Acoustic Technique	ITC	Leaks	>12 inch
12	seismic pulse echo	ITC	Wire breaks, delamination, and cracks	>=54 inch
13	Remote- Field Eddy Current: RFEC	ITC	Remaining wall thickness, wire breaks	6- 18 inch
14	Remote Field inspection	ITC	Remaining wall thickness, wire breaks	Any
15	Remote- Field Eddy Current/ Transformer Coupling: RFEC/ TC	ITC	Wire Breaks	16- 56 Inch

16	SmartBall	ITC	Leak	>10 Inch
17	In- Line investigation Ultrasonic Pigs	ITC	Wall thickness	>6 Inch
18	Leak Pigs	ITC	Leaks	Any
19	Caliper pig	ITC	Pipeline defects, pipeline geographical location and orientation	Any
20	water audit	OMC	Leaks	Any
21	Soil corrosivity Measurements	OMC	Corrosion	Any
22	Permalog	OTC	Leaks	Any
23	Piezo Structural Acoustic Pipeline Leak Detection system	OTC	Leaks	Any
24	The Urchin	OTC		Any
25	Smart Sensors	OTC	Optimizing and monitoring structural performance	Any
26	Smart Structure	OTC	Optimizing and monitoring structural performance	Any
27	Fibre Sensor Technology	OTC	Wire breaks	Any

Where

ETC- External Condition Assessment Technologies

ITC- Internal Condition Assessment Technologies

OMC- Other Methodologies

OTC- Emerging Technologies

Pipe Components

Condition Assessability Index value is a combination of Condition Assessability Index values for various pipe components. Each Pipe Component's Condition Assessability index is calculated by tracking backwards the various data parameters which need to be collected and how they can be collected.

The Various Pipe components and their respective distress indicators of PCCP pipes are listed below:

1. External Mortar Coating: The distress indicators of External Mortar Coating are Spalling, Crack, and Corrosion.
2. Internal Mortar Coating: The distress indicators of Internal Mortar Coating are Spalling, Crack, Coloration and Corrosion.
3. Pre-stressed Wire: The distress indicators of Pre-stressed Wire are Loss of protective layer around wires, Wire corrosion and Wire breaks.
4. Concrete Core: The distress indicators of Concrete Core are Delamination, Crack and Corrosion.
5. Steel Cylinder: The distress indicators of Steel Cylinder are Corrosion, Pin Hole and Crack.
6. Joints: The distress indicators of Joints are Change in Alignment, Joint Displacement, Joint Diaper, Joint Leaks, and Joint Corrosion.
7. Deformed Pipes
8. Leaks: The distress indicators are Core Leak and Joint Leak.

The various failure modes of the pipe components have been explained and studied while developing the predictability index.

Evaluation of Condition Assessability Index

Condition Assessability Index is a combination of two indices: Performance Analysis and Economic Analysis. These indices are in the range 1 to 5.

The Condition Assessability Index for the PCCP Water Mains is evaluated. The Condition Assessability index, listed as per the distress indicator is included in the appendix. The list of appendices is shown in Table 21.

Table 21: List of Appendix for Condition Assessability Index

The Distress Indicator	Appendix
Internal Mortar Coating	M
External Mortar Coating	N
Pre-stressed Wire	O
Concrete Core	P
Steel Cylinder	Q
Joint	R
Leaks	S
Deformed pipe	T

Deduction of Common and Innovative Condition Assessment Technologies for various Pipe Components

The objective of Condition Assessability index is to give two common and two innovative condition assessment technologies for the high-risk the pipe is prone to. The Condition Assessability indices are values associated with various pipe components. Thereby by the pipe component which is more prone to high-risk the Condition Assessability index would suggest two common and two innovative condition assessment technologies for various pipe components. These technologies are listed in Table 22.

Table 22: The Common and Innovative Technologies associated with detecting the failure of various pipe components

Pipe Components	Common Technologies	Innovative Technologies
Internal Mortar Coating	Remote Field Eddy Current, Remote Field Inspection	In-line investigation Ultrasonics Pig, Seismic Pulse Echo
External Mortar Coating	Eddy Current Inspection	Smart Sensors, Smart Structure
Concrete Core	Seismic Pulse Echo, Eddy Current Inspection	Smart Sensors
Pre-stressed Wire	Seismic Pulse Echo, Remote Field Eddy Current	Fibre Sensor Technology
Steel Cylinder	Seismic Pulse Echo, Eddy Current Inspection	Smart Sensors
Joints		Caliper Pig
Leaks	Water Audit, Acoustic Leak Detectors	SmartBall, Sahara
Deformed Pipe	Visual Inspection	Caliper Pig

CHAPTER 8. VALIDATION OF THE MODEL- WSSC CASE STUDY

Washington Suburban Sanitary Commission is one of the biggest utilities in the United States. It operated and maintains 4 reservoirs (Triadelphia, Rocky Gorge, Little Seneca and Jennings Randolph with total holding capacity of 14 billion gallons), 2 water filtration plants (the Patuxent (max 56 MGD) and the Potomac (max 285 MGD) plants produce an average of 167 million gallons per day (MGD) of safe drinking water), 6 wastewater treatment plant (Western Branch, Piscataway, Parkway, Seneca, Damascus and Hyattstown, with a total capacity to handle 74.1 million gallons of wastewater per day), the Blue Plains Water Pollution Control Plant handles as much as an additional 169 MGD under a cost sharing agreement with the WSSC and nearly 5,500 miles of water main lines and over 5,300 miles of sewer main lines.

WSSC has approximately 400 miles of PCCP pipelines in water and sewer use with 150 miles of PCCP 36-96 inch diameter in water service. The ages of PCCP water mains range from 30 to 60 years with an average age of 45 years. Approx. 40 miles of WSSC PCCP were made with Class IV wire which are high-risk pipelines. WSSC has replaced critical 72-in and 84-in PCCP that had Class IV wire with Steel pipes and smaller diameter DIP. Currently WSSC has 6 miles per year PCCP water pipeline condition assessment program using internal inspection and testing. 6 miles of Fiber Optic cable are also installed inside the pipeline for continuous monitoring. WSSC has been instrumental in the development of PCCP inspection and testing methods including visual/sounding, seismic pulse echo, and P-wave electromagnetic.

The predictability index and Condition Assessability index have been modified after visit to WSSC and getting all relevant PCCP failure information. The predictability index has been modified considering the various WSSC PCCP failures.

The major changes are listed below for better understanding:

1. The list needs to be sub-divided into various levels. This is considering the fact that none of the utilities can collect all the 80 data parameters required for the prediction model. This implies there is a need for development of a procedure that could help the utility decides on the data parameters they should concentrate on collecting.

2. Classification of the wires is a parameter that has been added to the data parameters. The wire classification is important as the class of wire defined the risk associated with the pipe in consideration.
3. Addition of "carbon-dioxide corrosion" to the data parameters since WSSC had observed corrosion of the mortar coating. Carbon dioxide reacts with the mortar layer forming a carbonate layer, which is separated from the pipe layer.
4. Division of the Predictability Index as ECP and LCP depending on what kind of pipe it is, following the flow chart initially indicated.

WSSC Risk Model

WSSC follows a risk factor with six parameters to evaluate their pipes. The procedure followed helps them make a priority among pipe for decisions towards further inspection. The risk factors are:

- Land Use Factor (LF): The Land Use Factors have been listed in Table 23.

Table 23: Land Use Factors of WSSC Model

Description	Rating Factor
Limited Damage Caused by pipe rupture	0
Home water damage greater than 75ft from pipe or down stream	1
Structural Damage , limited use road	2
Major road likely flooding	3
Home within 75 ft of pipe- potential structural damage	4
Commercial facility likely water damage	5
Commercial facility within 75ft of pipe- potential structural damage	6
Major road- Structural Damage	7
Bridge Structural Damage	8
Other Risk assigned upon evaluation	?

- Repair History (RH)
- Operational Needs (ON): The Operational Needs are listed in Table 24.

Table 24: Operational Needs of WSSC Model

Description	Rating Factor
Local Effect Only	1
Water Restriction during peak demand	2
Water Restriction in non peak Demand	8

- Known Manufacturing Defects (KD): Manufacturing Defects are listed in Table 25.

Table 25: Known Manufacturing Defects of WSSC Model

Description	Rating
Lap Joint Weld (pipe greater than 60”)	1
Class III 8 ga pre 1991	1
36” and greater in diameter lined cylinder pipe	2
Poured concrete coating	3
Class IV wire 5/16 diameter	3
Class IV wire ¼ diameter	4
Class IV wire 6 ga (post 1977)	5
Class IV wire 6 ga (pre 1977)	6
Class IV wire 8 ga (post 1977)	6
Class IV wire 8 ga (pre 1977)	7
Grade E Cylinder	

- Last Inspected (LI): The Last Inspected values are listed in Table 26.

Table 26: Last Inspected Values of WSSC Model

Description	Rating
Less than 5 years ago	1
5 to 8 years ago	2
9 to 12 years ago	3
13 to 15 years ago	4
16 to never	5

- Diameter (DI): The diameter factor values are listed in Table 27.

Table 27: The Diameter Factors of WSSC Model

Description	Factor
42” or less	0
42” to 54”	2
60” to 66”	4
72” to 78”	6
78” and greater	8

The combined risk factors

- General form
    - Defects* Operational Needs
- Empirical Formula
    - Risk- (RH+DI+KD)*(ON*4+LI)(LF)
- The factors DI, RH and KD are included in the predictability of the pipe barrel.

- The Factors ON and LF are included in the high-risk scenario and high-risk situations.

The combined risk factor formula does not have an upper limit. But WSSC considers any value above 80 to be at risk and a value above 100 to be at greater risk. This range is explained in Figure 50.

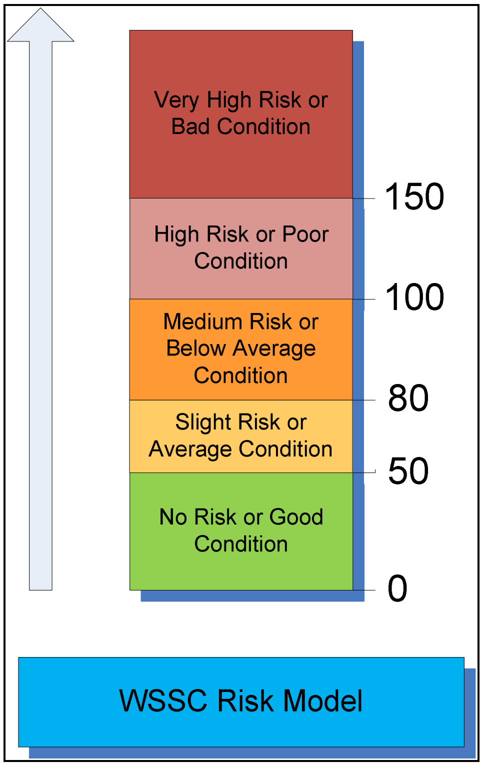

Figure 50: WSSC Risk Model Range

By studying and understanding the model used by WSSC for their risk assessment, one can understand the type of risks their pipelines are prone to. Most of the factors in this risk formula are factors considering the high-risk situations and scenarios faced by the pipeline system.

Factors like diameter and operational needs guides the utility towards the high-risk scenarios of the pipeline. Factors like the known manufacturing defects and land-use guides the utility towards the high-risk situations the pipelines exist in.

Sample Calculations of ***Predictability Index*** in comparison with WSSC Case Study

Predictability Index has been calculated for various pipe contracts in WSSC. And the value thus obtained has been compared with the value obtained with the WSSC model. This exercise has been done to understand the shortcomings of either the Predictability Index or WSSC, if any. For the evaluation of the Predictability index, some parameters were considered from the data existent with WSSC.

The data parameters collected are:

- Type of PCCP pipe: The pipe being embedded cylinder pipe or lined cylinder pipe notes the difference in failure mechanisms.
- Diameter of the pipe: Defines the risk involves if the pipe breaks. Higher diameter implies higher risk.
- Pipe Class: Based on standard, pre-stressed wire, etc.
- Year of manufacturing of the pipe: this data helps in two ways. Firstly, estimate the life of the pipe against the design life. Secondly, to identify with the data of common failure observed. This is related with manufacturing defects associated with the time of manufacturing.
- Location of the pipe: This data provides us information if the pipe is in high-risk scenario or not.
- Wire Class: Wire class directly helps depict the risk associated with the pipes.
- Wire Properties: The observed wire properties to the design give the strength of the wire.
- Pressures: The various pressures, i.e. the working pressure, surge pressure, etc., observed when compared to the design pressures gives the strength the pipe can withstand.
- Inspection report: The inspection report has data like detected leaks, reports of visual inspections, condition assessment, etc.

- Action observed: actions observed gives us data of repair and rehabilitation done in the pipe. This helps us understand any unusual behavior of the pipe performance.

WSSC Case Study

Case study for 25 different pipe contracts has been performed and a trend has been observed. Complete case studies and evaluation have been included in Appendix L. The trend is illustrated in Figure 51. The values obtained by the predictability index are of the same level or higher than the WSSC values. WSSC model mainly considers high-risk situation/scenarios more when compared to the pipe structural properties/strength. Therefore the predictability index captures those cases with high predictability or risk for failure, which WSSC model does not. Also, WSSC model does not have adequate data for all pipes. This could be observed when further case studies were done to compare values of WSSC and predictability index.

The Predictability and Condition Assessability indices calculations have been performed with the data from WSSC. However, the complete data is not used by WSSC for its own risk model. The proposed Predictability index can use any amount of data towards predicting the failure of the pipe and thus is a robust model.

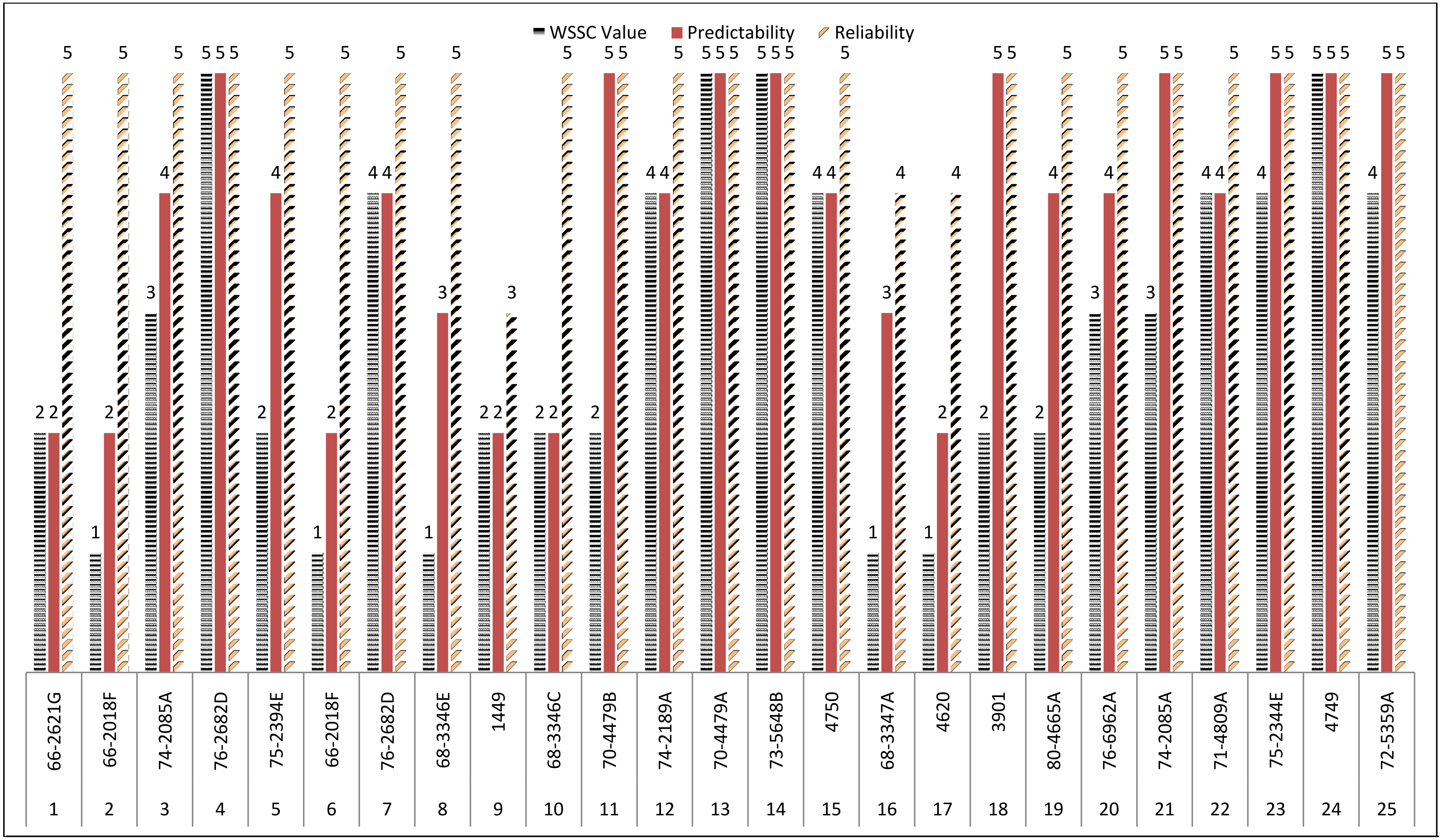

Figure 51: Comparative values of WSSC Model against Predictability Index

Advantages of Predictability Index in comparison with WSSC model

Various case studies performed over WSSC pipes indicate that the proposed Predictability index better predicts failure over WSSC model. WSSC model primarily considers high-risk situations and scenarios as its input parameters. In order to enhance the model with more parameters, further empirical experiments have to be performed. However, Predictability index can accommodate the data. Though predictability index considers over 70 parameters, it could still be used even with the lack of complete dataset. Since Predictability index is accompanied by the reliability index, it simultaneously reflects on the confidence of data. The graph in Figure 46 contains the reliability of the derived predictability. There are very few cases with reliability less than 5. This clearly indicates that WSSC has high confidence in their data. However, there have not been able to use this data appropriately in the risk model. This is evident from the comparative study between the WSSC model and Predictability index. There have been cases where WSSC risk model and Predictability Index have concluded the same. But there have also been cases where Predictability index has predicted higher risk than the WSSC model. However, the reverse case has not occurred where Predictability index has predicted lower risk than the WSSC model. However, the predictability index results in more false positive than the WSSC risk model.

Condition Assessment Technologies Used by WSSC

WSSC have been very active in the area of condition assessment technologies. They have listed their condition assessment technologies in the following way as shown in Table 28.

Table 28: Condition Assessment Technologies Used by WSSC

Inside the Pipe	**Outside the Pipe**
Visual Inspections ❖ CCTV ❖ Combination CCTV/ NDE sledge ❖ Walk Inspection	Acoustic monitoring
Seismic Pulse Echo	Excavation, then: ❖ Visual ❖ Seismic pulse echo ❖ Broadband Magnetics ❖ Ultrasonics ❖ Wire Sampling
Magnetics	
Acoustic monitoring	
Ultrasonics	

Calculate the Condition Assessability Index for pipeline in WSSC for two common and two innovative condition assessment approaches

The Condition Assessability index values are fixed numbers for a particular distress indicator of the given material. Of the various pipes in consideration from the case study, pipe contract no: 76-2682D is one of the pipelines that needs special attention for technologies specific to the risk faced by the pipe.

Condition Assessability of Pipe I: Contract no 76-2682 D

Since the predictability index of the high-risk pipe-I has a predictability of "5" and reliability of "5". The pipe has a high probability of failing and the reliability of the associated data has high reliability. This gives the utility the knowledge of where investment towards inspection and monitoring is required. When the predictability is backtracked, going back every stage to understand the reason for such high predictability one can track which area needs more focus.

Based on the index values obtained and the data contained by the utility the main risks faced by the pipe in consideration are:

1. Wire Breaks because of low Wire Class
2. High risk scenario / situation
3. Lower Quality of Water
4. Leaks

The Condition Assessability indices are constant for a given pipe material and distress indicator. In the given case, the probable failure modes and distress indicators have been identified. The associated Condition Assessability indices are:

The Condition Assessability of wire breaks is:

- Performance- “3”, Economic Analysis-“3”.

The Condition Assessability of Leaks is:

- Performance-“4”, Economic Analysis-“3”.

The Condition Assessability indices are a combination of the performance and economic analysis. The Condition Assessability index value of any particular distress indicator is accompanied by a list of technologies and/or methodologies associated with for collecting data and further inspections. These lists of technologies help the utilities to identify the two common condition assessment approaches and two innovative condition assessment approaches. The approaches identified for the given high risk pipe are:

The two common condition assessment approaches are:

1. Acoustic Testing (Wire breaks, concrete composition)
2. Visual Inspections, Water Audits (Leaks, mud, etc.)

Two innovative condition assessment approaches are:

1. Optical Fibers (leaks, wire breaks, third party damage, etc.)
2. Sahara Acoustic and Smart-Ball (Leaks)

Condition Assessability of Pipe II: Contract no 68- 3346E 1969

This particular pipe in consideration is in the same contract as Case Study 7. That pipe was found to be at very low risk as per the WSSC risk model and at medium risk as per the Predictability index. This particular pipe, however, has failed on June 15, 2008. Table 29 provides the details about the pipe.

Table 29: Pipe Description Pipe: Contract 68- 3346E

Diameter	**48 inch**
Type of pipe	Embedded Cylinder Pipe
Wire class	II
Concrete Class	B
Slope of pipe	26 Deg approx
Location	Down the hillside. Eroded over the years.
	Right of ways are over grown with large trees
	Carbon-dioxide in soil
	Near Rock Creek

This particular pipe is in high risk. Since, the soil contains carbon-dioxide and is near rock creek the pipe is in high-risk. Based on the index values obtained and the data contained by the utility the main risks faced by the pipe in consideration are:

1. Corrosion in Soils
2. High risk scenario / situation
3. Clear Right of Way

The Condition Assessability indices are constant for a given pipe material and distress indicator. In the given case, the probable failure modes and distress indicators have been identified. And the associated Condition Assessability indices are:

The Condition Assessability of External Mortar Coating is:

- Performance-“4”, Economic Analysis-“3”.

The Condition Assessability indices are a combination of the performance and economic analysis. The Condition Assessability index value of any particular distress indicator is accompanied by a list of technologies and/or methodologies associated with for collecting data and further inspections. These lists of technologies help the utilities to identify the two common condition assessment approaches and two innovative condition assessment approaches. The approaches identified for the given high risk pipe are:

The common condition assessment approaches are:

1. Eddy Current Inspection (External Mortar Coating)
2. Soil Testings (Soil effect on External Mortar)
3. Seismic Pulse Echo (Concrete Core)

The innovative condition assessment approaches are:

1. Smart Sensors/ Structures

Condition Assessability of Pipe with low predictability index

The Condition Assessability indices are constant for a given pipe material and distress indicator. Considering cases where the predictability index is low or very low, the Condition Assessability of any particular high-risk or distress indicator is not possible. In such cases, the Condition Assessability index considers general condition assessment. The associated Condition Assessability indices are:

The Condition Assessability of Low or Very Low risk pipes is:

- Performance-“3”, Economic Analysis-“3”.

The Condition Assessability indices are a combination of the performance and economic analysis. The Condition Assessability index value in cases with low predictability considers general condition assessment technologies to continue validation of the predictability. The approaches identified for the given pipe condition are:

The common condition assessment approaches are:

1. Eddy Current Inspection
2. Seismic Pulse Echo

The innovative condition assessment approaches are:

1. Smart Sensors/ Structures
2. Fibre sensor technology

WSSC Case Study Conclusion

The result obtained by WSSC and that by Condition Assessability Index are not very different. This is because WSSC is well equipped with the various latest technologies available in the market. And have been actively participating in the development of the latest technologies.

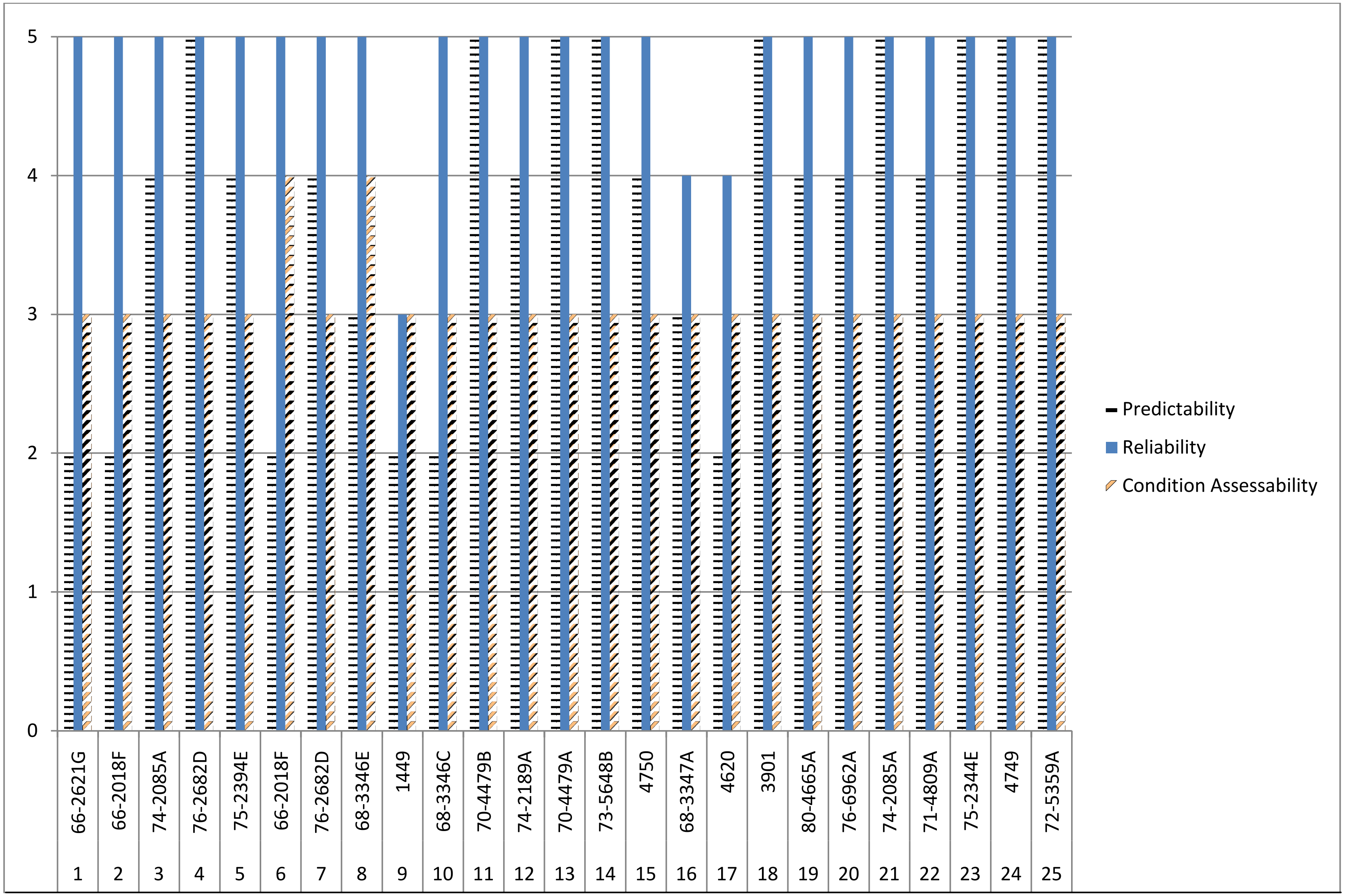

Figure 52: Predictability and Condition Assessability Indices of high-risk pipes in WSSC

For appropriate assessment of condition assessability, one should appropriately assess the predictability index and find out of which component is in higher risk. In this particular case study, the condition assessability index is “3” in most cases as shown in Figure 52. This observation has been made since the high-risk associated with most of the pipes is due to the pre-stressed wire. The cases with high-risk external mortar and low predictability have condition assessability index value “4”.

Though there exists high knowledge of condition assessment technologies and in most cases the predictability is predicted appropriated with high confidence data, the condition assessability index is not 5 in any case. This is because condition assessability index considers both economic and performance factors for evaluating the condition assessability. It is practically not feasible to perform condition assessment for all the pipes in the utility. Hence the low values of Condition Assessability index.

Conclusion

Condition Assessability Indices are fixed numbers. These are derived from the knowledge of state-of-the-art technologies. Condition Assessability Indices are like charts which give the utilities an idea about the kind of technology they should use when they have a certain high-risk. But understanding and using the condition assessability indices appropriately, one should evaluate the pipe components in high-risk and the distress indicators the pipe is prone to. Without accurate evaluation of the high-risk of the pipe, appropriate prevention is not possible. Hence, it is important to detect the possible distress indicators appropriately.

CHAPTER 9. CONCLUSION

Use of the proposed Predictability and Condition Assessability Indices (Funding agencies, Researchers, Consultants, and Utilities)

The Predictability & Condition Assessability Indices will guide the utilities to better understand their system and help them determine the condition assessment procedure they need to follow. The Indices help various funding agencies to determine the possible scope for future development. They will help the technologies developers to understand the need of better technologies for more efficient technologies and methodologies. The researchers will be provided with a base of the understanding about the pipe systems, various materials, failure modes and mechanisms, and the factors attributing towards this. This will form base for future research and provide higher understanding of the pipe system.

Predictability index and Condition Assessability index account to various parameters. Predictability index has three levels depending on the amount of data the utility can collect. The index calculation is not hampered by the non-existence of complete data. However, the reduced data input reflects on the reliability index of the predictability index.

Further Research

Although, the predictability index though has provided results close to the results of the WSSC study, needs further improvement. This index has been verified on WSSC PCCP case study for different scenarios of low-risk, high-risk and extremely high-risk. However, its results may vary depending on the utility in consideration for calculating index. Therefore, data of other utilities would help further validation of the model.

For the calculation of predictability, if severity/ occurrence value of any of the contributing factors is not greater than 3, then the index calculates using weighted average. These formulae can be validated further or modified only by using the index in various situations.

WSSC Study has helped us identify new data parameters like Carbon dioxide in soil, etc. Further study with other utilities may help identify parameters that are more critical and develop robust PCCP indices. In the WSSC case study, the data (with confidence of 3 or more) input for the calculation of the index is around 25-35%. However, the reliability of the data is “5”. The consistency in the reliability is a result of same number of input parameters in both the case. The reliability of the index in this study had still a value of “5” despite the number of parameters considered being low. This is because the parameters captured the most relevant data when compared to the kind of problems faced by WSSC, for example; poor pre-stressing and/or poor grade of the wire. The logic behind the reliability may be verified with other utilities, as the problems faced are different for different utilities because of operational and environmental factors.

For Condition Assessability index, the condition assessment technologies may be evaluated over their performance with respect to the indicators. Both lack of indicators and lack of feasible data collection methods or technologies would lead to lesser Condition Assessability index. Data may be collected from the vendors to make appropriate calculation for the Condition Assessability. The study of the condition assessment technologies may be done considering, the type of data the technologies would be used for collecting and the different types of data the technologies would collect against the cost of installation and running of the technologies. Upon providing different weights to the parameters defined for Condition Assessability, the Condition Assessability index can be arrived at.

The gap between the technologies can be identified after the analysis by identifying the various high-risk situations with least Condition Assessability. The predictability and Condition Assessability index should be developed for the remaining pipe materials.

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Appendix A: List of Pipe Inspection Technologies

The list of pipe inspection technologies are listed in Table 30. Table 30 includes also includes critical details of the technology or methodology

Table 30: List of Technologies and Methodologies

		Leaks Detection	Thickness	External Assessment	Internal Assessment	Corrosion	Wire Breaks
1	water audit	yes					
2	Soil corrosivity Measurements			yes		yes	
3	half-cell measurement			yes		yes	
4	visual inspection and sounding				yes		yes
5	acoustic emission monitoring				yes		yes
6	RFEC		yes		yes		yes
7	RFEC/ TC		yes		yes		yes
8	Magnetic Flux	yes	yes		yes		
9	broadband electromagnetic		yes	yes			
10	ultrasonic inspection		yes		yes		
11	long range ultrasonic		yes	yes			
12	eddy current inspection	yes	yes	yes	yes		
13	infrared and Thermography	yes		yes			
14	acoustic leak detection	yes					
15	seismic pulse echo		yes		yes		
16	Smart Sensor	yes	yes	yes	yes	yes	yes

		Leaks Detection	Thickness	External Assessment	Internal Assessment	Corrosion	Wire Breaks
17	Smart Structure	yes	yes	yes	yes	yes	yes
18	Fibre Sensor: interferometric, polarimetric and modal interferometric sensors	yes	yes	yes	yes	yes	yes
19	Impact Echo			yes	yes		
20	Manhole condition assessment: visual				yes		
21	Ground penetration Radar			yes			
22	In- Line investigation Ultrasonic Pigs		yes		yes		
23	Guided wave Ultrasonic systems		yes			yes	
24	Super Pig		yes		yes		
25	Electro Magnetic Acoustic Transducer	yes	yes	yes			
26	Permalog	yes					
27	Non- Contact Ultrasonics			yes			
28	Magic Carpet	yes		yes			
29	Piezo Structural Acoustic Pipeline Leak Detection system	yes					
30	Sahara	yes			yes		

		Leaks Detection	Thickness	External Assessment	Internal Assessment	Corrosion	Wire Breaks
	Acoustics						
31	Smart-Ball	yes			yes		
32	Remote Field inspection	yes	yes	yes	yes	yes	
33	Inductive Profiling	yes		yes			
34	Leak Pigs	yes			yes		
35	Magnetic detection			yes			
36	Caliper pig				yes		
37	Sonde and Receiver Technique			yes			
38	Magnetic Flux Leakage Pig				yes	yes	
39	X-Ray External Surface	yes		yes		yes	
40	Acoustic Loggers	yes			yes		
41	Leak Noise Correlators	yes			yes		

Appendix B: Internal Condition Assessment Technologies

The list of internal condition assessment technologies are included in Table 31.

Table 31: List of Internal Condition Assessment Technologies

S.No	Technology	Assessment parameter	Material	Diameter	Maximum Range(ft)	Inspection Rate (ft/min)*	Advantage	Limitations
1	visual inspection and sounding	Leaks, Wire breaks	All, PCCP	Large Diameters			Longest record of successfully detecting damaged pipes	requires man entry into pipes
								does not give direct information on wire breaks in pre-stressed concrete pipes
								unclear whether all wire breaks produce noticeable concrete damage
								subjective in nature and dependant on skill of inspection team

S.No	Technology	Assessment parameter	Material	Diameter	Maximum Range(ft)	Inspection Rate (ft/min)*	Advantage	Limitations
2	Leak Noise Correlators	leaks	any	any			system offers leak detection from surface using pipeline features	other techniques are required to determine if the leak is from the joint or pipe barrel and the system is not effective on large diameter pipes
3	acoustic leak detection	Leakage	Any	>12	6500	0.2	Avoid disruption of the water supply to the customer	Inspection range can be limited by pipeline geometry (number of bends)
							Wide diameter range	works best for metal water pipes
							Known to find leak accurately	Background noise problems
							Requires only a small diameter access point	Gives only present condition (less in predictability)
4	acoustic emission monitoring	Wire Breaks	PCCP	>= 24	5280	600	Inserted into water main under pressure, no interruption to supply	web enabled reporting system provides event information

S.No	Technology	Assessment parameter	Material	Diameter	Maximum Range(ft)	Inspection Rate (ft/min)*	Advantage	Limitations
							can detect wire breaks during monitoring period and locate them	only detects damage that occur during monitoring period
							works in all types of pre-stressed concrete pipes	
5	Acoustic Loggers	leaks	any	any			readily identify an area of leakage, which can then be pinpointed with noise correlators	requires experience for interpretation of data and other techniques will be required to determine if joint or pipe barrel leakage
6	Sahara Acoustic Technique	Locates Leaks	Plastic or nonmetallic mains	>12	6000		can be used where there is change in material	Costs 2- 4 $/ ft
							Can be used where there are changes in diameter along the length	

S.No	Technology	Assessment parameter	Material	Diameter	Maximum Range(ft)	Inspection Rate (ft/min)*	Advantage	Limitations
							used in main with limited connection points	
							can be used where multiple leaks are suspected	
7	ultrasonic inspection	Wall thickness	Steel, Cast iron, and ductile iron	All			No interruption to supply, non- intrusive technique	Can only be used where pipe is exposed or by digging access pits
							It can detect and size corrosion pits	technique will not work through tuberculation
								requires access to and complete cleaning of the pipes
8	seismic pulse echo	Wire breaks, delamination, and cracks	PCCP	>= 54		4	Successfully identifies defects in PCCP	Requires dewatering and man entry into the pipe

S.No	Technology	Assessment parameter	Material	Diameter	Maximum Range(ft)	Inspection Rate (ft/min)*	Advantage	Limitations
							Can be used to determine baseline prior to use of online monitoring	Is not non-interruptive
								Not currently available in diameters below 54 inch (1400mm)
9	Remote- Field Eddy Current: RFEC	remaining wall thickness, wire breaks	Steel, cast iron, ductile iron	6,8,10,12,15,16 and 18	3000	20	established technology dates back to early 1990s	Pipe requires cleaning prior to inspection
			PCCP				Available to suit a range of pipe diameters	cost of removing material dislodged by cleaning is high
							100% examination of pipe wall	necessary to discharge water to the environment during survey
							assessment possible in wet or dry pipe	

S.No	Technology	Assessment parameter	Material	Diameter	Maximum Range(ft)	Inspection Rate (ft/min)*	Advantage	Limitations
10	Remote Field inspection	remaining wall thickness, wire breaks	metallic and PCCP				Detects areas of corrosive pitting, as well as through holes	more expensive than leak detection
							can be used to give an estimate of the future life of the line	requires access to the inside of the water line, which may require cleaning
							can detect single or multiple broken wires	knowledge of the relationship between pit size and residual life of the pipe is not yet complete
							inspection gives complete picture of damage to the pipeline	model evaluated by NRC would not detect pits of less than 3000 cu.m in size
11	Remote- Field Eddy Current/ Transformer Coupling: RFEC/ TC	Wire Breaks	PCCP	16 to 256			Detects single or multiple pre-stressing wires	requires dewatering of pipes

S.No	Technology	Assessment parameter	Material	Diameter	Maximum Range(ft)	Inspection Rate (ft/min)*	Advantage	Limitations
								Requires human entry into pipes
12	eddy current inspection	wall loss and other pipeline defects	Any	Any			All joints are located on a long run	Water pipe may require prior cleaning and will require a launch and receive facility.
13	Magnetic Flux	Wall thickness, Leakage, Corrosion	Cast iron, ductile iron, steel	>3		67-787	No interruption to supply, non- intrusive technique	Can only be used where pipe is exposed or by digging access pits
							Can detect small defects and through holes in metal pipes	requires access to and complete cleaning of the pipes
							joints are located on a long run	
14	Sonde and Receiver technique	track the pipe and allow positions of joints to be detected and marked from above	non-metallic pipes	any			joints are located on a long run	system requires an in-pipe launch facility

S.No	Technology	Assessment parameter	Material	Diameter	Maximum Range(ft)	Inspection Rate (ft/min)*	Advantage	Limitations
		ground						
15	Smart-Ball	Leak	All types of pressure pipe, including concrete, steel, ductile iron, PVC, an GRP	>10			Can work on wide range of pipe types	
							There is no apparatus noise, hence can detect small leaks	
							Long lengths of pipe can be surveyed	
16	In- Line investigation Ultrasonic Pigs	Wall thickness	All	>6		395	directly measures wall thickness	

S.No	Technology	Assessment parameter	Material	Diameter	Maximum Range(ft)	Inspection Rate (ft/min)*	Advantage	Limitations
							differentiates between internal and external wall thickness	
							detects cracking	
17	Super Pig	will identify wall thickness loss to 1mm, longitudinal and circumferential cracks, damage to linings, and leaks	ferrous	08 to 12			The pig can operate with a water main in service but needs special launch and recovery facilities which need to be retrofitted to the line	close fit Polyethylene linings and thicker linings such as cement mortar present difficulties
								Pretty expensive
18	Leak Pigs	Leaks	all				all leakages would be detected over the long pipe run	The system may also scrape loose deposits from the pipe wall, leading to potential water quality problems

S.No	Technology	Assessment parameter	Material	Diameter	Maximum Range(ft)	Inspection Rate (ft/min)*	Advantage	Limitations
								launch and receive facilities are required and the pipeline would need to be decommissioned
19	Caliper pig	pipeline defects, pipeline geographical location and orientation	All				joints are located on a long run	system requires a launch and receive facility

Appendix C: External Condition Assessment Technologies

The list of external condition assessment technologies are included in Table 32.

Table 32: List of External Condition Assessment Technologies

S.No	Technology	Assessment parameter	Material	Diameter	Maximum Range(ft)	Inspection Rate (ft/min)*	Advantage	Limitations
1	half-cell measurement	Corrosion	Any	Any			simple to conduct	factors such as stray current and soil conditions may affect readings
							may act as a screening mechanism for more expensive methods	accuracy of results depends on distance between readings
							well established as method to detect corrosion activity in buried objects	small areas of localized corrosion cannot be detected
2	Magnetic Detection	identify joints, wall thickness	steel, cast iron				light, portable and can identify joints in a rural environment with experience	Considerable interference from other metallic street furniture and vehicles, and depth of mains.
3	Electro Magnetic Acoustic Transducer	Cracks and Pipe Thickness	ferrous	Any			The advantage of such a tool is that it does not need a couplant. EMAT is dry coupled and suited to gas pipelines.	it needs to be very close (1mm) to the pipe surface
4	broadband electromagnetic	Remaining wall thickness	Steel, Cast Iron, Ductile Iron	>=3	2000	9 to 11	able to survey through external coating and internal linings	requires pipe to be depressurized during the assessment and full bore access

S.No	Technology	Assessment parameter	Material	Diameter	Maximum Range(ft)	Inspection Rate (ft/min)*	Advantage	Limitations
							No upper limit on pipe diameter	Inspection rate in only a few feet per day in large diameters
5	Inductive Profiling	Leaks	All	Any			totally a non-contact, non-invasive technology	More Resistive soil, the penetration is lower
6	eddy current inspection	wall loss and other pipeline defects	Any	Any		L	All joints are located on a long run	Water pipe may require prior cleaning and will require a launch and receive facility.
7	long range ultrasonic	Pipe wall cross-section	Steel	2 to 48	100		No interruption to supply, non- intrusive technique	Can only be used where pipe is exposed or by digging access pits
								Only reports reduction in pipe wall cross section, not deepest pit
								could miss a critical defect
8	Guided wave Ultrasonic systems	Corrosion	ferrous, Plastic	any	262		can identify all butt joints, non intrusive	Single joint only for mechanical joints. Requires excavation for buried pipe.
9	infrared and Thermography	Leak	All	Any		3 to 100 mi/ day	Totally a non-contact, non-invasive method	cannot determine a pipe's state of health before a failure
								Above ground structures can easily mask the IR camera form the pipeline

S.No	Technology	Assessment parameter	Material	Diameter	Maximum Range(ft)	Inspection Rate (ft/min)*	Advantage	Limitations
10	Ground penetration Radar	Detects delamination of concrete pipes	Concrete	Any			Helps examine the bedding of the pipes	certain soil types and water table variations can attenuate the signal
							It is capable of identifying a wide range of defects including internal and external metal loss and cracking	The transmitted low frequency ultrasonic energy is a limitation on range
11	Magic Carpet	leaks	Any	Any			An alternative to noise correlators	Sensitive to background noise and other techniques are required to distinguish between joint or pipe barrel leakage

Appendix D: Other Methodologies for Condition Assessment

The list of other methodologies are included in Table 33.

Table 33: List of Other Methodologies for Condition Assessment

S.No	Technology	Assessment parameter	Material	Diameter	Maximum Range(ft)	Inspection Rate (ft/min)*	Advantage	Limitations
1	water audit	Leaks	Any	Any			also tracks illegal connections	Cannot by themselves locate leaks accurately
							Covers large area quickly	requires isolation of zones
							used as screening process for other technologies	work must be performed at night
							can be used to evaluate effectiveness of repair techniques	only gives current overview of problem
							Inexpensive	
2	Soil corrosivity Measurements	Corrosion	Any	Any			simple to conduct	cities may have similar levels of corrosivity across their region, making use difficult
							may act as a screening mechanism for more expensive methods	there is no clear correlation between corrosion measurements and number of pipe breaks
3	Pipe Sample Removal							

S.No	Technology	Assessment parameter	Material	Diameter	Maximum Range(ft)	Inspection Rate (ft/min)*	Advantage	Limitations
4	Coupon removal	Type and extent of corrosion						

Appendix E: Emerging Technologies for Condition Assessment

The list of emerging technologies of condition assessment are included in Table 34.

Table 34: List of Emerging Condition Assessment Technologies

S.No	Technology	Assessment parameter	Material	Diameter	Maximum Range(ft)	Inspection Rate (ft/min)*	Advantage	Limitations	Comments
1	Permalog	Leaks	All	Any			timely review can be done	Gives general location does not accurately detect the Leak	
2	Piezo Structural Acoustic Pipeline Leak Detection system	Leaks							these technologies are widely used in the oil and gas pipeline systems but are still in emerging stages for water and wastewater pipe infrastructures
3	Wire line Acoustics	Breaks in pre-stressed wires							
4	The Urchin								
5	radiography		Ferrous pipe	>15					
6	Non- Contact Ultrasonic's								

S.No	Technology	Assessment parameter	Material	Diameter	Maximum Range(ft)	Inspection Rate (ft/min)*	Advantage	Limitations	Comments
7	liquid penetrant testing								
8	Smart Sensors	optimizing and monitoring structural performance	All	any	any				
9	Smart Structure	monitoring loading criteria and performance	All	any	any			problem with low-pressure pipe work	
10	X-ray external surface	corrosion, leaks, cracks	steel	any			it can identify cracks, areas of corrosion, partial leak paths	operationally it is difficult to deploy and requires excavation	

S.No	Technology	Assessment parameter	Material	Diameter	Maximum Range(ft)	Inspection Rate (ft/min)*	Advantage	Limitations	Comments
11	Fiber Sensor Technology: interferometric, polarimetric and modal interferometric sensors		All	any	any				Ability to function without need for direct electrical power, ability to transmit relatively weak signals over long distances without deterioration and the capacity to make distributed measurements.

Appendix F: Evaluation of Severity/ Occurrence and Reliability of Influencing Factors from input data and Source of the Data (Stage 1)

Table 35 illustrates the evaluation of severity/occurrence and reliability of influencing factors from input data and source of the data.

Table 35: Evaluation of Severity/ Occurrence and Reliability of Influencing Factors from input data and Source of the Data

						This is where the data is to be included by the users	**Here the Users have to justify their data by specifying their level on confidence on the data**		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
		The stage of the pipe's life where the required data is to be collected	**Explanation of the inputs that are required**				Direct Data- 5, Incomplete Data- 4, Indirect Data-3, Educated Guess- 2, No Data-1	Very High- 5, High- 4, Medium- 3, Low- 2, Very Low- 1	Very High- 5, High- 4, Medium-3, Low- 2, Very Low- 1
1	Lining thickness/ design thickness	Manufacturing, Installation, Operations	The ratio of the present lining thickness to the design lining thickness	Ratio	0 onwards (Ideally 1)	0.5	4	5	4

						This is where the data is to be included by the users	Here the Users have to justify their data by specifying their level on confidence on the data		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
	Manufacturing								
2	Manufacturing Inspection	Manufacturing	Manufacturing Inspection is inspection for cracks in pipes before the pipes are sent for installation	Level	inspected and no cracks-2, inspected and minor cracks-1, inspected and major cracks-0, not inspected- 1	1	4	3	4
3	Curing Time/ Design Curing time	Manufacturing	the ratio of the curing time provided for the concrete against the design concrete curing time	Ratio	0 onwards (Ideally 1)	0.5	3	5	3
4	cement content/ design cement content	Manufacturing	The ratio of the observed cement content in the pipe against the design cements content. This is done by taking samples and testing	Ratio	0 onwards (Ideally 1)	1.2	3	2	3
5	Wire manufacturing	Manufacturing	Wire should not be overheated while drawing lines. Wire manufacturing inspection needs to be	Level	1-5	4	3	4	3

						This is where the data is to be included by the users	**Here the Users have to justify their data by specifying their level on confidence on the data**		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
			done						
6	Wire Class	Manufacturing	The Class of the wire defines the strength of the wire	Grade	I-1, II-2, III-3, IV-4	2	5	3	5
7	Elastic limit/ working pressure	Manufacturing		ratio	2.25		2	3	2
8	Wire tensile strength	Manufacturing		psi	80000	6000	4	4	4
Installation									
9	Encasement	Installation	The presence of encasement	Yes/ No	Yes-1, No- 0	1	4	3	4
10	Design Constructability	Installation	The design constructability is the level of difficulty faced by the constructing professionals for laying the pipes	Level	1-5, with 1 being the easy to construct and 5 being difficult to construct	3	4	3	4

						This is where the data is to be included by the users	**Here the Users have to justify their data by specifying their level on confidence on the data**		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
11	Installation Inspection/ Orderly Installation	Installation	Inspection is required at various phases of the pipe's life. Installation Inspection is the inspection whether the pipes are being laid in the right order as designated.	level	Inspected and installed perfectly-2, Inspected and not installed perfectly-1, Not inspected- 0	0	5	4	5
12	Installation inspection for leaks and cracks	Installation	Inspection is required at various phases of the pipe's life. Installation Inspection is the inspection whether the pipes laid are not leaking	level	Inspected and installed perfectly-2, Inspected and not installed perfectly-1, Not inspected- 1	0	5	4	5
13	Post Transportation Inspection	Installation	In transportation, there are chances of rough handling which may lead to cracking of the pipes.	Level	inspected and no cracks-2, inspected and minor cracks-1, inspected and major cracks-0, not inspected- 3	1	4	3	4

						This is where the data is to be included by the users	Here the Users have to justify their data by specifying their level on confidence on the data		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
14	Weld	Installation	Welding process is a very skillful process and need constant inspection for the final product	Level	inspected and properly welded-2, inspected and minor faults-1, inspected and major faults-0, not inspected- 3	2	4	1	4
15	External Coating	Installation	Presence of external coating	Yes/no-Type	Yes-1, No- 0	1	3	1	3
16	joint fit up	Installation	The joint fittings should be inspected whether done properly	Level	Joint fitting inspected and fitted properly-2, joint fitting not inspected-1, joint fitting inspected and force fitted- 0	0	5	4	5
17	Joint coating	Installation	The presence of joint coating has to be installed	Level	Presence of joint coating- 2, presence of joint coating but not well coated-1, no joint coating-0	1	4	3	4

						This is where the data is to be included by the users	**Here the Users have to justify their data by specifying their level on confidence on the data**		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
18	PCCP differences	Installation	There are differences in the type of PCCP used in the same network	Level			4	3	4
19	Concrete Strength/ Design Strength	Installation	Ratio of the cast pipe strength to the design strength	Ratio	0 onwards (Ideally 1)	0.75	3	3	3
20	Aggregate size/design size	Installation	Ratio of the aggregate size to the design aggregate size	Ratio	0 onwards (Ideally 1)	1.2	3	2	3
21	Carbonation of concrete	Installation	Whether concrete was carbonated or not	yes/ No	Yes- 1, No- 0	1	5	4	5
22	Difference in pH	Installation	Difference in pH	level	0-5	3	4	5	4
23	Water Cement Ratio/ Design Water Cement Ratio	Installation	The ratio of the water cement ratio to the design water cement ratio	ratio	0 onwards (Ideally 1)	1.1	3	1	3
24	Hydro test Pressure/ Design Pressure	Installation, Operations	The Ratio of the Hydrotest pressure to the design pressure of the pipe. Greater Hydrotest pressure cracks the coating	Ratio	0 onwards (Ideally 1)	0.8	3	1	3

						This is where the data is to be included by the users	Here the Users have to justify their data by specifying their level on confidence on the data		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
	Operations								
24	soil resistivity	Operations	The ratio of the present soil resistivity to the min soil resistivity required in soil (3000 ohm-cm)	ohm cm	0- 12000	2000	3	2	3
25	Wire Breaks	Operations	The count of wire breaks	Dia-48" : number	Breaks>= 41-5, 21<=Breaks<40-4, 6<=breaks<20-3,<5 breaks-2, no breaks-1	4	3	4	3
				Dia-96" : number	Breaks>= 81-5, 41<=Breaks<80-4, 11<=breaks<40-3,<10 breaks-2, no breaks-1	4	3	4	3
26	Surge Pressure/ Design Pressure	Operations	The Ratio of the observed surge pressure over the design pressure of the pipe	Ratio	0 onwards (Ideally 1)	5	4	5	4

						This is where the data is to be included by the users	Here the Users have to justify their data by specifying their level on confidence on the data		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
27	Load(dead load + live load)/ Design Load	Operations	The ratio of the load acting on the pipe to the load it is designed for	Ratio	0 onwards (Ideally 1)	5	4	5	4
28	Alkali Reactivity Tested/ Design Alkali Reactivity	Operations	The Ratio of the tested alkali reactivity of the concrete against the design alkali reactivity	Ratio	0 onwards (Ideally 1)	1.3	5	4	5
29	ppm of chlorides in soil/700ppm	Operations	The ratio of the present chloride content in soil to the acceptable level of 700 ppm	Ratio	0 onwards (Ideally 1)	1.1	4	2	4
30	Bedding Stiffness/design stiffness	Operations	The ratio of the present bedding stiffness to the designed stiffness of the bedding	Ratio	0 onwards (Ideally 1)	0.5	3	5	3
31	pipe restraint	Operations					1	3	1
32	concrete core stiffness/ spigot ring stiffness	Operations					5	2	5

						This is where the data is to be included by the users	Here the Users have to justify their data by specifying their level on confidence on the data		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
33	Pipe location	Operations	Pipe in soil or whether it is outside soil	Level	Pipe completely in Soil- 2, Pipe partially in Soil-1, Pipe completely outside-0	2	3	3	3
34	Pipe Age/ Design Life of the pipe	Operations	The age of the pipe is not a direct measure	Ratio	0 onwards (Ideally 1)	4	3	5	3
35	Pipe Depth	Operations	Depth of the Pipe from surface	Ft				4	
36	Thrust Restraint	Operations		Yes-No/ Type			5	3	5
37	Soil Type	Operations					2	2	2
38	Climate-Temperature	Operations	Temperature of the Soil	F			4	3	4
39	Loading Condition (Dead Load)	Operations	The Dead Load acting on the pipeline system	lbs/sq.ft			3	4	3
40	Loading Condition (Live Load)	Operations	The Live load acting on the pipeline system	lbs/sq.ft			2	5	2

						This is where the data is to be included by the users	Here the Users have to justify their data by specifying their level on confidence on the data		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
41	Aggressive Water	Operations	The presence of aggressive water flow through the pipeline system	Yes-1/no-0			3	1	3
42	Soil Corrosivity	Operations	Soil corrosivity is influenced by various factors namely soil type, soil disturbance, soil pH, soil resistivity, red-ox potential, chloride content, chloride content, microbial influenced				1	3	1
43	Soil pH	Operations	The range should be 5-8 anything else could give rise to soil corrosivity	pH	0-14	4	1	2	1
44	Soil Chloride	Operations	The content of chloride in the soil. It is measured on a percentage scale	%			1	4	1
45	Soil Sulphate	Operations	The content of sulphate in the soil. It is measured on a percentage scale	%			5	2	5

						This is where the data is to be included by the users	Here the Users have to justify their data by specifying their level on confidence on the data		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
46	Soil sulfide	Operations	The content of sulfide in the soil. It is measured on a percentage scale	%			5	3	5
47	Soil Eration	Operations					3	4	3
48	Soil porosity	Operations					4	5	4
49	Groundwater Table	Operations	The level of groundwater table	Ft			2	3	2
50	Frost Penetration	Operations					4	4	4
51	Soil Moisture Content	Operations	The level of moisture content of the soil	Level	Poor Drainage Continuously wet-2, fairly drainage generally moist-1, good drainage generally dry- 0		3	4	3
52	Water Corrosivity	Operations					1	2	1
53	Stray Currents	Operations	Presence of stray currents				5	4	5
54	Soil Disturbance	Operations	Disturbed soil may lead to aeration of soil, which leads to soil corrosivity	yes/ no-level	Highly disturbed soil- 2, Slightly disturbed soil- 1, Undisturbed soil-0		3	2	3

						This is where the data is to be included by the users	**Here the Users have to justify their data by specifying their level on confidence on the data**		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
55	Non Uniform Soil	Operations	The presence of non uniform Soil	Yes/ No			4	3	4
56	Runoff Rate	Operations	The run off changes the behavior of the soil and the other surroundings with interaction with the pipe	cu.ft/sec.			2	4	2
57	Concrete Exposed to moisture/ Cl-	Operations	The % of concrete core exposed to moisture and chloride has to be below the limit of 0.10%	%	0.001		4	5	4
58	Concrete exposed to moisture without Cl-	Operations	The % of concrete core exposed to moisture without chloride has to be below the limit of 0.15%	%	0.0015		4	3	4
59	Corrosion of steel reinforcements	Operations	The observations of corrosion leads to concrete data to support failure of the pipe				3	2	3

						This is where the data is to be included by the users	Here the Users have to justify their data by specifying their level on confidence on the data		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
60	Crack Type	Operations	There are different types of cracks	Type	Longitudinal (Spring Line)- 5, Mixed (long+circum)-4, Longitudinal (crown/ invert)-3, Circumferential-2, No Crack- 1	4	3	4	3
61	Crack Width	Operations	The width of the crack indicates it seriousness	mm	>= 10 mm - 5, >=5mm- 4, >=1mm- 3, Hairline- 2, No cracks-1	4	3	4	3
62	Crack Density	Operations	The spacing between the cracks	mm	Crack Spacing>= 100mm -5, Crack spacing>50-4, Crack Spacing<=50-3,	4	3	4	3

						This is where the data is to be included by the users	Here the Users have to justify their data by specifying their level on confidence on the data		
No:	Influencing Factors	Stage of the pipe life	Explanation for factors	Unit	Range	Input	Source of Input	Severity/ Occurrence	Reliability
					No cracks-1				
63	Sound Test	Operations	Hammer Tapping sound, Hollow Sound, No Sound	Type	Very Firm Tapping Sound-5, Firm Tapping Sound-4, Slightly Hollow Tapping Sound-3, Moderately Hollow Sound-2, Very Hollow Sound-1, No Sound-0	4	3	4	3
64	Pipe Geometry	Operations	Shape of the pipe is a clear indicator of the structure of the pipe		Bulge> 3% of the diameter- 5, Bulge between 2% and 3% of the diameter-4, Bulge between 1% and 2% of the diameter- 3, Bulge< 1% of the diameter- 2, No Bulge-1	4	3	4	3

						This is where the data is to be included by the users	Here the Users have to justify their data by specifying their level on confidence on the data		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
65	Alignment of the pipe	Operations	The alignment of the pipe when compared to the actual placement of the pipes	Type	Angle>22.5 or alignment>11%- 5, 6%< alignment<10%-4, angle<22.5 or alignment<5%- 3, No change-1	4	3	4	3
66	Joint Displacement	Operations	The joints can be displaced without undergoing joint misalignment	Type	Joint displaced- 1, Joint not displaced- 0		4	3	4
67	Joint diaper crack size	Operations	The diaper crack width is measured	Type	>= 10 mm - 5, >=5mm- 4, >=1mm- 3, Hairline- 2, No cracks-1	4	3	4	3
68	Delamination	Operations	The existence of delamination	Type	Yes- 2, May be-1, No-0	1	3	3	3
69	Coloration	Operations	The Color of the mortar coating is a clear indicator of the condition of the concrete layer	Type	Obvious Rust Strains-5, Moderate Rust Strains-4, Slight Rust Strains-3, No	4	3	4	3

						This is where the data is to be included by the users	Here the Users have to justify their data by specifying their level on confidence on the data		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
					Strains-1				
70	Hollow Area	Operations	The existence of Hollow area indicates weakness in the structure	Type	Hollow area>= 6%-5, 4%<= Hollow Area<6%-4, 2%<=Hollow Area<4-3, Hollow Area<2%-2, No Hollow Area-1	4	3	4	3
71	Leaks	Operations	The volume of leak is measured to verify if it is in the acceptable range	Gallon/ Min	0 onwards	5	4	5	4

Appendix G: Evaluation of Predictability and Reliability of the Failure Paths from the Influencing Factors (Stage 2)

Table 36 illustrates the evaluation of predictability and reliability of the failure paths from the influencing factors.

Table 36: Evaluation of Predictability and Reliability of the Failure Paths from the Influencing Factors

The Index of Severity and occurrence along with the reliability index are being derived from the influencing factor's severity, occurrence and reliability. This calculation is automatic and considers the weights specified as per the possible failure path				
Pred	**Rel**	**s.no**	**Failure Paths**	**Weights**
5	**4**	**a**	Impact load on rigid surface- mortar cracking	Loading Conditions+ design load
4	**5**	**b**	Poor Constructability of the design=> poor construction practices=>cracked lining and coating	Construction inspection+ design constructability+ installation inspection
4	**5**	**c**	Pipe Laid out of order=> under designed or over designed=> cracks/bending	Installation + Variation in design strengths + difference in beddings
4	**5**	**d**	Rough handling of pipe(wet coat, transportation, placing in the trench) => Cracking of the coating	manufacturing inspection+ post transportation inspection
4	**4**	**e**	Uneven Mortar=> Flushing of Protective alkalinity from around the wire	manufacturing inspection+ lining thickness
4	**4**	**f**	Pipe encased throughout its circumference- dissimilarity in bedding stiffness- differential settlement circumferential cracks	Encasement+ bedding stiffness
4	**5**	**g**	Inadequate or improper curing prior to prestressing => Coating shrinkage=> exposure of wire reinforcement=> corrosion	Curing time+ installation inspection+ post transportation inspection
4	**3**	**h**	Wire breaks and Splicing=> loss of pre-stress	Wire breaks
3	**4**	**i**	Hydrotest Pressures> Design pressures/Design Surge Pressure- Coating Cracks	Hydrotest pressure+ design pressure

The Index of Severity and occurrence along with the reliability index are being derived from the influencing factor's severity, occurrence and reliability. This calculation is automatic and considers the weights specified as per the possible failure path				
Pred	**Rel**	**s.no**	**Failure Paths**	**Weights**
2	**4**	**j**	Chlorides in Soil> 700ppm - Loss of protective environment around pre-stressed wire	Chloride in soil
2	**3**		Soil resistivity< 3000 ohm-cm => Loss of protective environment around pre-stressed wire	Soil resistivity
2	**3**	**l**	Low Quality of mortar- Wire Corrosion	Mortar quality+ water cement ratio+ cement content
2	**3**	**m**	Low density of core- wire corrosion	Mortar quality+ water cement ratio+ cement content
4	**5**	**n**	low thickness of core- wire corrosion	Mortar quality+ water cement ratio+ cement content+ thickness or core
5	**2**	**o**	low cement content- wire corrosion	Mortar quality+ water cement ratio+ cement content
5	**4**	**p**	Over Pressuring- Coating cracks- Wires exposed to water- wires corrode and break- pressure in transferred to the cylinder- core cracks- cylinder exposed to water- cylinder corrodes and fails	pressure+ design pressure+ water exposure+ corrosive soils
4	**5**	**q**	Core Under designed=> loss of pre-stress	concrete strength+ design strength
4	**4**	**r**	Overheating of wire during drawing leads => poor torsion ductility and susceptibility to hydrogen embrittlement	wire manufacturing + strength
5	**5**	**s**	Alkali Reactivity and Poor concrete strength- Low Quality Cores	Alkali reactivity + concrete strength +design strength+ core strength
2	**3**	**t**	High Water Cement ratio => excessive core creep and shrinkage	Mortar quality+ water cement ratio+ cement content
3	**3**	**u**	Too Many fine aggregates=> excessive core creep and shrinkage	aggregate size+ core strength
5	**4**	**v**	Inadequate or improper curing prior to prestressing => excessive core creep and shrinkage	curing time+ core strength

The Index of Severity and occurrence along with the reliability index are being derived from the influencing factor's severity, occurrence and reliability. This calculation is automatic and considers the weights specified as per the possible failure path				
Pred	**Rel**	**s.no**	**Failure Paths**	**Weights**
2	**3**	**w**	High Water Cement ratio => Coating shrinkage=> exposure of wire reinforcement=> corrosion	Mortar quality+ water cement ratio+ cement content
3	**3**	**x**	Too Many fine aggregates=> Coating shrinkage=> exposure of wire reinforcement=> corrosion	aggregate size+ core strength
5	**5**	**y**	Carbonation of concrete=>differences in pH=> increased crevice corrosion	carbonation of concrete+ pH differences
3	**4**	**z**	Variation of the PCCP cores=> Cracks	variation in PCCP core
4	**5**	**aa**	Unnoticed construction damage=> leaking joints(need field inspection)	Installation inspection
4	**5**	**ab**	Missing joint coating=> leaking joints	Joint Coating +installation inspection
4	**5**	**ac**	Cracks in joint weld=> leaking joints	welding+ installation inspection
4	**5**	**ad**	Looped gasket=> leaking joints	gasket inspection+ installation inspection
4	**5**	**ae**	Poor joint fit up=> leaking joints	Joint fit up+ installation inspection
2	**5**	**af**	Inadequate pipe restraint- mechanically restrained joints- opened of mortared joints- steel joint ring exposed to corrosion- steel joint ring corroded- steel joint expands and cracks the coating-exposes the wire	Pipe restraint + joint restraints+ corrosive soils+ core strength
4	**5**	**ag**	Mis-fit of joints/ out of roundness of the mating joints => leaking of the joints	joints fitting
4	**3**	**ah**	Cracking of the core at the joints=> Leaking at the joints	core cracking at joints

The Index of Severity and occurrence along with the reliability index are being derived from the influencing factor's severity, occurrence and reliability. This calculation is automatic and considers the weights specified as per the possible failure path				
Pred	**Rel**	**s.no**	**Failure Paths**	**Weights**
2	**5**	**ai**	Stiffness Discontinuity between pre-stressed core and the unstressed spigot ring => circumferential cracks in the thin part of the core at the junction of the cylinder and the spigot	stiffness discontinuity
3	**3**	**aj**	Fabrication Errors=> dented pipes	fabrication errors+ installation inspection+ design constructability
5	**3**	**ak**	Poor Welds=> defective cylinders	welding+ installation inspection

Appendix H: Evaluation of Predictability and Reliability of the Various Distress Indicators (Stage 3)

Table 37 illustrates the evaluation of predictability and reliability of various distress indicators.

Table 37: Evaluation of Predictability and Reliability of Various Distress Indicators

Predictability	**Reliability**	**S.No**	**Distress Indicators**	**Weights**
I Interior Mortar Coating				
3	5		Spalling	weathering+ corrosion
4	5		Crack	b+ d+ f+ i
4	3		Coloration	69
4	5		Corrosion	crack+ corrosive properties
II Exterior Mortar Coating				
5	5		Spalling	a+ weathering+ corrosion
5	5		Crack	a+ b+ c+ d+ f+ i
4	3		Coloration	69
5	5		Corrosion	crack+ corrosive properties
III Steel Cylinder				
5	5		Corrosion	
5	5		Pin hole	
5	5		Crack	
IV Pre-stressed Wire				
5	5		Loss of protective layer around wires	e+ g+ h+ j+ k+ crack+ q
5	5		Wire Corrosion	l+ m+ n+ o
5	5		Wire Breaks	g+ r+ loss of protective layer+ wire corrosion

Predictability	**Reliability**	**S.No**	**Distress Indicators**	**Weights**
V Concrete Core				
5	5		Delamination	s+ w+ x
5	5		Crack	s+ t+ u+ v+ z
5	5		Corrosion	s+ w+ x+ y
VI Joint Failure				
4	3		Change in Alignment	65
3	4		Joint displacement	66
4	5		Joint Diaper	ai + 67
5	5		Joint Leaks	aa+ ab+ ac+ ad+ ae+ ag+ ah+ ak
2	5		Joint Corrosion	af
5	3	VII	Deformed Pipes	aj+ ak
5	5	VIII	Leaks	leaked joints + cracked core

Appendix I: Predictability Index for Embedded Cylinder PCCP Water Mains

There are 6 Stages for the calculation of predictability index of a PCCP water main.

Stage 1: Evaluation of Severity/ Occurrence and Reliability of Data Parameters

Table 38 illustrates the Stage 1 calculations of the predictability index for the embedded cylinder PCCP water mains.

Table 38: Stage 1 Calculations of the Predictability Index for Embedded Cylinder PCCP Water Mains

						This is where the data is to be included by the users	**Here the Users have to justify their data by specifying their level on confidence on the data**		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
		The stage of the pipe's life where the required data is to be collected	**Explanation of the inputs that are required**				Direct Data- 5, Incomplete Data-4, Indirect Data-3, Educated Guess-2, No Data-1	Very High- 5, High- 4, Medium-3, Low- 2, Very Low- 1	Very High- 5, High- 4, Medium-3, Low- 2, Very Low- 1
1	Lining thickness/ design thickness	Manufacturing, Installation, Operations	The ratio of the present lining thickness to the design lining thickness	Ratio	0 onwards (Ideally 1)	0.5	4	5	4

						This is where the data is to be included by the users	**Here the Users have to justify their data by specifying their level on confidence on the data**		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
Manufacturing									
2	Manufacturing Inspection	Manufacturing	Manufacturing Inspection is inspection for cracks in pipes before the pipes are sent for installation	Level	inspected and no cracks-2, inspected and minor cracks-1, inspected and major cracks-0, not inspected- 1	1	4	3	4
3	Curing Time/ Design Curing time	Manufacturing	the ratio of the curing time provided for the concrete against the design concrete curing time	Ratio	0 onwards (Ideally 1)	0.5	3	5	3
4	cement content/ design cement content	Manufacturing	The ratio of the observed cement content in the pipe against the design cements content. This is done by taking samples and testing	Ratio	0 onwards (Ideally 1)	1.2	3	2	3
5	Wire manufacturing	Manufacturing	Wire should not be overheated while drawing lines. Wire manufacturing inspection needs to be done	Level	1-5	4	3	4	3

						This is where the data is to be included by the users	**Here the Users have to justify their data by specifying their level on confidence on the data**		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
6	Wire Class	Manufacturing	The Class of the wire defines the strength of the wire	Grade	I-1, II-2, III-3, IV-4	2	5	3	5
7	Elastic limit/ working pressure	Manufacturing		ratio	2.25		2	3	2
8	Wire tensile strength	Manufacturing		psi	80000	6000	4	4	4
Installation									
9	Encasement	Installation	The presence of encasement	Yes/ No	Yes-1, No- 0	1	4	3	4
10	Design Constructability	Installation	The design constructability is the level of difficulty faced by the constructing professionals for laying the pipes	Level	1-5, with 1 being the easy to construct and 5 being difficult to construct	3	4	3	4
11	Installation Inspection/ Orderly Installation	Installation	Inspection is required at various phases of the pipe's life. Installation Inspection is the inspection whether the pipes are being laid in the right order as designated.	level	Inspected and installed perfectly-2, Inspected and not installed perfectly-1, Not inspected- 0	0	5	4	5

						This is where the data is to be included by the users	Here the Users have to justify their data by specifying their level on confidence on the data		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
12	Installation inspection for leaks and cracks	Installation	Inspection is required at various phases of the pipe's life. Installation Inspection is the inspection whether the pipes laid are not leaking	level	Inspected and installed perfectly-2, Inspected and not installed perfectly-1, Not inspected- 1	0	5	4	5
13	Post Transportation Inspection	Installation	In transportation, there are chances of rough handling which may lead to cracking of the pipes.	Level	inspected and no cracks-2, inspected and minor cracks-1, inspected and major cracks-0, not inspected- 3	1	4	3	4
14	Weld	Installation	Welding process is a very skillful process and need constant inspection for the final product	Level	inspected and properly welded-2, inspected and minor faults-1, inspected and major faults-0, not inspected- 3	2	4	1	4
15	External Coating	Installation	Presence of external coating	Yes/no -Type	Yes-1, No- 0	1	3	1	3

						This is where the data is to be included by the users	**Here the Users have to justify their data by specifying their level on confidence on the data**		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
16	joint fit up	Installation	The joint fittings should be inspected whether done properly	Level	Joint fitting inspected and fitted properly-2, joint fitting not inspected-1, joint fitting inspected and force fitted- 0	0	5	4	5
17	Joint coating	Installation	The presence of joint coating has to be installed	Level	Presence of joint coating- 2, presence of joint coating but not well coated-1, no joint coating-0	1	4	3	4
18	PCCP differences	Installation	There are differences in the type of PCCP used in the same network	Level			4	3	4
19	Concrete Strength/ Design Strength	Installation	Ratio of the cast pipe strength to the design strength	Ratio	0 onwards (Ideally 1)	0.75	3	3	3
20	Aggregate size/design size	Installation	Ratio of the aggregate size to the design aggregate size	Ratio	0 onwards (Ideally 1)	1.2	3	2	3

						This is where the data is to be included by the users	**Here the Users have to justify their data by specifying their level on confidence on the data**		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
21	Carbonation of concrete	Installation	Whether concrete was carbonated or not	yes/ No	Yes- 1, No- 0	1	5	4	5
22	Difference in pH	Installation	Difference in pH	level	0-5	3	4	5	4
23	Water Cement Ratio/ Design Water Cement Ratio	Installation	The ratio of the water cement ratio to the design water cement ratio	ratio	0 onwards (Ideally 1)	1.1	3	1	3
24	Hydrotest Pressure/ Design Pressure	Installation, Operations	The Ratio of the Hydrotest pressure to the design pressure of the pipe. Greater Hydrotest pressure cracks the coating	Ratio	0 onwards (Ideally 1)	0.8	3	1	3
Operations									
24	soil resistivity	Operations	The ratio of the present soil resistivity to the min soil resistivity required in soil (3000 ohm-cm)	ohm cm	0- 12000	2000	3	2	3
25	Wire Breaks	Operations	The count of wire breaks	Dia- 48" : number	Breaks>= 41-5, 21<=Breaks<40-4, 6<=breaks<20-3,<5 breaks-2, no breaks-1	4	3	4	3

						This is where the data is to be included by the users	Here the Users have to justify their data by specifying their level on confidence on the data		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
				Dia-96" : number	Breaks>= 81-5, 41<=Breaks<80-4, 11<=breaks<40-3,<10 breaks-2, no breaks-1	4	3	4	3
26	Surge Pressure/ Design Pressure	Operations	The Ratio of the observed surge pressure over the design pressure of the pipe	Ratio	0 onwards (Ideally 1)	5	4	5	4
27	Load(dead load + live load)/ Design Load	Operations	The ratio of the load acting on the pipe to the load it is designed for	Ratio	0 onwards (Ideally 1)	5	4	5	4
28	Alkali Reactivity Tested/ Design Alkali Reactivity	Operations	The Ratio of the tested alkali reactivity of the concrete against the design alkali reactivity	Ratio	0 onwards (Ideally 1)	1.3	5	4	5
29	ppm of chlorides in soil/700ppm	Operations	The ratio of the present chloride content in soil to the acceptable level of 700 ppm	Ratio	0 onwards (Ideally 1)	1.1	4	2	4
30	Bedding Stiffness/design stiffness	Operations	The ratio of the present bedding stiffness to the designed stiffness of the	Ratio	0 onwards (Ideally 1)	0.5	3	5	3

						This is where the data is to be included by the users	Here the Users have to justify their data by specifying their level on confidence on the data		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
			bedding						
31	pipe restraint	Operations					1	3	1
32	concrete core stiffness/ spigot ring stiffness	Operations					5	2	5
33	Pipe location	Operations	Pipe in soil or whether it is outside soil	Level	Pipe completely in Soil- 2, Pipe partially in Soil-1, Pipe completely outside-0	2	3	3	3
34	Pipe Age/ Design Life of the pipe	Operations	The age of the pipe is not a direct measure	Ratio	0 onwards (Ideally 1)	4	3	5	3
35	Pipe Depth	Operations	Depth of the Pipe from surface	Ft				4	
36	Thrust Restraint	Operations		Yes-No/ Type			5	3	5
37	Soil Type	Operations					2	2	2
38	Climate- Temperature	Operations	Temperature of the Soil	F			4	3	4

						This is where the data is to be included by the users	**Here the Users have to justify their data by specifying their level on confidence on the data**		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
39	Loading Condition (Dead Load)	Operations	The Dead Load acting on the pipeline system	lbs/sq.ft			3	4	3
40	Loading Condition (Live Load)	Operations	The Live load acting on the pipeline system	lbs/sq.ft			2	5	2
41	Aggressive Water	Operations	The presence of aggressive water flow through the pipeline system	Yes-1/no-0			3	1	3
42	Soil Corrosivity	Operations	Soil corrosivity is influenced by various factors namely soil type, soil disturbance, soil pH, soil resistivity, red-ox potential, chloride content, chloride content, microbially influenced				1	3	1
43	Soil pH	Operations	The range should be 5-8 anything else could give rise to soil corrosivity	pH	0-14	4	1	2	1
44	Soil Chloride	Operations	The content of chloride in the soil. It is measured on a percentage scale	%			1	4	1

						This is where the data is to be included by the users	**Here the Users have to justify their data by specifying their level on confidence on the data**		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
45	Soil Sulphate	Operations	The content of sulphate in the soil. It is measured on a percentage scale	%			5	2	5
46	Soil sulfide	Operations	The content of sulfide in the soil. It is measured on a percentage scale	%			5	3	5
47	Soil Eration	Operations					3	4	3
48	Soil porosity	Operations					4	5	4
49	Groundwater Table	Operations	The level of groundwater table	Ft			2	3	2
50	Frost Penetration	Operations					4	4	4
51	Soil Moisture Content	Operations	The level of moisture content of the soil	Level	Poor Drainage Continuously wet-2, fair drainage generally moist-1, good drainage generally dry- 0		3	4	3
52	Water Corrosivity	Operations					1	2	1
53	Stray Currents	Operations	Presence of stray currents				5	4	5

						This is where the data is to be included by the users	Here the Users have to justify their data by specifying their level on confidence on the data		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
54	Soil Disturbance	Operations	Disturbed soil may lead to aeration of soil, which leads to soil corrosivity	yes/ no-level	Highly disturbed soil- 2, Slightly disturbed soil- 1, Undisturbed soil-0		3	2	3
55	Non Uniform Soil	Operations	The presence of non uniform Soil	Yes/ No			4	3	4
56	Runoff Rate	Operations	The run off changes the behavior of the soil and the other surroundings with interaction with the pipe	cu.ft/sec.			2	4	2
57	Concrete Exposed to moisture/ Cl-	Operations	The % of concrete core exposed to moisture and chloride has to be below the limit of 0.10%	%	0.001		4	5	4
58	Concrete exposed to moisture without Cl-	Operations	The % of concrete core exposed to moisture without chloride has to be below the limit of 0.15%	%	0.0015		4	3	4
59	Corrosion of steel reinforcements	Operations	The observations of corrosion leads to concrete data to support failure of the pipe				3	2	3

						This is where the data is to be included by the users	**Here the Users have to justify their data by specifying their level on confidence on the data**		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
60	Crack Type	Operations	There are different types of cracks	Type	Longitudinal (Spring Line)- 5, Mixed (long+circum)-4, Longitudinal (crown/ invert)-3, Circumferential-2, No Crack- 1	4	3	4	3
61	Crack Width	Operations	The width of the crack indicates it seriousness	mm	>= 10 mm - 5, >=5mm- 4, >=1mm- 3, Hairline- 2, No cracks-1	4	3	4	3
62	Crack Density	Operations	The spacing between the cracks	mm	Crack Spacing>= 100mm -5, Crack spacing>50- 4, Crack Spacing<=50-3, No cracks-1	4	3	4	3

						This is where the data is to be included by the users	**Here the Users have to justify their data by specifying their level on confidence on the data**		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
63	Sound Test	Operations	Hammer Tapping sound, Hollow Sound, No Sound	Type	Very Firm Tapping Sound-5, Firm Tapping Sound-4, Slightly Hollow Tapping Sound-3, Moderately Hollow Sound-2, Very Hollow Sound-1, No Sound-0	4	3	4	3
64	Pipe Geometry	Operations	Shape of the pipe is a clear indicator of the structure of the pipe		Bulge> 3% of the diameter- 5, Bulge between 2% and 3% of the diameter-4, Bulge between 1% and 2% of the diameter- 3, Bulge< 1% of the diameter- 2, No Bulge-1	4	3	4	3

						This is where the data is to be included by the users	**Here the Users have to justify their data by specifying their level on confidence on the data**		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
65	Alignment of the pipe	Operations	The alignment of the pipe when compared to the actual placement of the pipes	Type	Angle>22.5 or alignment>11%- 5, 6%< alignment<10%-4, angle<22.5 or alignment<5%- 3, No change-1	4	3	4	3
66	Joint Displacement	Operations	The joints can be displaced without undergoing joint misalignment	Type	Joint displaced- 1, Joint not displaced- 0		4	3	4
67	Joint diaper crack size	Operations	The diaper crack width is measured	Type	>= 10 mm - 5, >=5mm- 4, >=1mm- 3, Hairline- 2, No cracks-1	4	3	4	3
68	Delamination	Operations	The existence of delamination	Type	Yes- 2, May be-1, No-0	1	3	3	3
69	Coloration	Operations	The Color of the mortar coating is a clear indicator of the condition of the concrete layer	Type	Obvious Rust Strains-5, Moderate Rust Strains-4, Slight Rust Strains-3, No Strains-1	4	3	4	3

						This is where the data is to be included by the users	Here the Users have to justify their data by specifying their level on confidence on the data		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
70	Hollow Area	Operations	The existence of Hollow area indicates weakness in the structure	Type	Hollow area>= 6%-5, 4%<= Hollow Area<6%-4, 2%<=Hollow Area<4-3, Hollow Area<2%-2, No Hollow Area-1	4	3	4	3
71	Leaks	Operations	The volume of leak is measured to verify if it is in the acceptable range	Gallon / Min	0 onwards	5	4	5	4

Stage 2 Evaluation of Severity/ Occurrence and Reliability of Failure Paths

Table 39 illustrates the Stage 2 calculations of the predictability index for the embedded cylinder PCCP water mains.

Table 39: Stage 2 Calculations of the Predictability Index for Embedded Cylinder PCCP Water Mains

The Index of Severity and occurrence along with the reliability index are being derived from the influencing factor's severity, occurrence and reliability. This calculation is automatic and considers the weights specified as per the possible failure path				
S/O	**R**	**s.no**	**Failure Paths**	**Weights**
5	**4**	**a**	Impact load on rigid surface- mortar cracking	Loading Conditions+ design load
4	**5**	**b**	Poor Constructability of the design=> poor construction practices=>cracked lining and coating	Construction inspection+ design constructability+ installation inspection
4	**5**	**c**	Pipe Laid out of order=> under designed or over designed=> cracks/bending	Installation + Variation in design strengths + difference in beddings
4	**5**	**d**	Rough handling of pipe(wet coat, transportation, placing in the trench) => Cracking of the coating	manufacturing inspection+ post transportation inspection
4	**4**	**e**	Uneven Mortar=> Flushing of Protective alkalinity from around the wire	manufacturing inspection+ lining thickness
4	**4**	**f**	Pipe encased throughout its circumference- dissimilarity in bedding stiffness- differential settlement circumferential cracks	Encasement+ bedding stiffness
4	**5**	**g**	Inadequate or improper curing prior to prestressing => Coating shrinkage=> exposure of wire reinforcement=> corrosion	Curing time+ installation inspection+ post transportation inspection
4	**3**	**h**	Wire breaks and Splicing=> loss of pre-stress	Wire breaks
3	**4**	**i**	Hydrotest Pressures> Design pressures/Design Surge Pressure- Coating Cracks	Hydrotest pressure+ design pressure

<table>
<tr><th colspan="5">The Index of Severity and occurrence along with the reliability index are being derived from the influencing factor's severity, occurrence and reliability. This calculation is automatic and considers the weights specified as per the possible failure path</th></tr>
<tr><th>S/O</th><th>R</th><th>s.no</th><th>Failure Paths</th><th>Weights</th></tr>
<tr><td>2</td><td>4</td><td>j</td><td>Chlorides in Soil> 700ppm - Loss of protective environment around pre-stressed wire</td><td>Chloride in soil</td></tr>
<tr><td>2</td><td>3</td><td></td><td>Soil resistivity< 3000 ohm-cm => Loss of protective environment around pre-stressed wire</td><td>Soil resistivity</td></tr>
<tr><td>2</td><td>3</td><td>l</td><td>Low Quality of mortar- Wire Corrosion</td><td>Mortar quality+ water cement ratio+ cement content</td></tr>
<tr><td>2</td><td>3</td><td>m</td><td>Low density of core- wire corrosion</td><td>Mortar quality+ water cement ratio+ cement content</td></tr>
<tr><td>4</td><td>5</td><td>n</td><td>low thickness of core- wire corrosion</td><td>Mortar quality+ water cement ratio+ cement content+ thickness or core</td></tr>
<tr><td>5</td><td>2</td><td>o</td><td>low cement content- wire corrosion</td><td>Mortar quality+ water cement ratio+ cement content</td></tr>
<tr><td>5</td><td>4</td><td>p</td><td>Over Pressuring- Coating cracks- Wires exposed to water- wires corrode and break- pressure in transferred to the cylinder- core cracks- cylinder exposed to water- cylinder corrodes and fails</td><td>pressure+ design pressure+ water exposure+ corrosive soils</td></tr>
<tr><td>4</td><td>5</td><td>q</td><td>Core Under designed=> loss of pre-stress</td><td>concrete strength+ design strength</td></tr>
<tr><td>4</td><td>4</td><td>r</td><td>Overheating of wire during drawing leads => poor torsion ductility and susceptibility to hydrogen embrittlement</td><td>wire manufacturing + strength</td></tr>
<tr><td>5</td><td>5</td><td>s</td><td>Alkali Reactivity and Poor concrete strength- Low Quality Cores</td><td>Alkali reactivity + concrete strength +design strength+ core strength</td></tr>
<tr><td>2</td><td>3</td><td>t</td><td>High Water Cement ratio => excessive core creep and shrinkage</td><td>Mortar quality+ water cement ratio+ cement content</td></tr>
<tr><td>3</td><td>3</td><td>u</td><td>Too Many fine aggregates=> excessive core creep and shrinkage</td><td>aggregate size+ core strength</td></tr>
</table>

The Index of Severity and occurrence along with the reliability index are being derived from the influencing factor's severity, occurrence and reliability. This calculation is automatic and considers the weights specified as per the possible failure path				
S/O	**R**	**s.no**	**Failure Paths**	**Weights**
5	**4**	**v**	Inadequate or improper curing prior to prestressing => excessive core creep and shrinkage	curing time+ core strength
2	**3**	**w**	High Water Cement ratio => Coating shrinkage=> exposure of wire reinforcement=> corrosion	Mortar quality+ water cement ratio+ cement content
3	**3**	**x**	Too Many fine aggregates=> Coating shrinkage=> exposure of wire reinforcement=> corrosion	aggregate size+ core strength
5	**5**	**y**	Carbonation of concrete=>differences in pH=> increased crevice corrosion	carbonation of concrete+ pH differences
3	**4**	**z**	Variation of the PCCP cores=> Cracks	variation in PCCP core
4	**5**	**aa**	Unnoticed construction damage=> leaking joints(need field inspection)	Installation inspection
4	**5**	**ab**	Missing joint coating=> leaking joints	Joint Coating +installation inspection
4	**5**	**ac**	Cracks in joint weld=> leaking joints	welding+ installation inspection
4	**5**	**ad**	Looped gasket=> leaking joints	gasket inspection+ installation inspection
4	**5**	**ae**	Poor joint fit up=> leaking joints	Joint fit up+ installation inspection
2	**5**	**af**	Inadequate pipe restraint- mechanically restrained joints- opened of mortared joints-steel joint ring exposed to corrosion- steel joint ring corroded- steel joint expands and cracks the coating-exposes the wire	Pipe restraint + joint restraints+ corrosive soils+ core strength
4	**5**	**ag**	Mis-fit of joints/ out of roundness of the mating joints => leaking of the joints	joints fitting

The Index of Severity and occurrence along with the reliability index are being derived from the influencing factor's severity, occurrence and reliability. This calculation is automatic and considers the weights specified as per the possible failure path				
S/O	**R**	**s.no**	**Failure Paths**	**Weights**
4	**3**	**ah**	Cracking of the core at the joints=> Leaking at the joints	core cracking at joints
2	**5**	**ai**	Stiffness Discontinuity between pre-stressed core and the unstressed spigot ring => circumferential cracks in the thin part of the core at the junction of the cylinder and the spigot	stiffness discontinuity
3	**3**	**aj**	Fabrication Errors=> dented pipes	fabrication errors+ installation inspection+ design constructability
5	**3**	**ak**	Poor Welds=> defective cylinders	welding+ installation inspection

Stage 3 Evaluation of Predictability and Reliability of Distress Indicators

Table 40 illustrates the Stage 3 calculations of the predictability index for the embedded cylinder PCCP water mains.

Table 40. Stage 3 Calculations of the Predictability Index for Embedded Cylinder PCCP Water Mains

Predictability	**Reliability**	**S.No**	**Distress Indicators**	**Weights**
I Interior Mortar Coating				
3	5		Spalling	weathering+ corrosion
4	5		Crack	b+ d+ f+ i
4	3		Coloration	69
4	5		Corrosion	crack+ corrosive properties
II Exterior Mortar Coating				
5	5		Spalling	a+ weathering+ corrosion
5	5		Crack	a+ b+ c+ d+ f+ i
4	3		Coloration	69

Predictability	**Reliability**	**S.No**	**Distress Indicators**	**Weights**
5	5		Corrosion	crack+ corrosive properties
III Steel Cylinder				
5	5		Corrosion	
5	5		Pin hole	
5	5		Crack	
IV Pre-stressed Wire				
5	5		Loss of protective layer around wires	e+ g+ h+ j+ k+ crack+ q
5	5		Wire Corrosion	l+ m+ n+ o
5	5		Wire Breaks	g+ r+ loss of protective layer+ wire corrosion
V Concrete Core				
5	5		Delamination	s+ w+ x
5	5		Crack	s+ t+ u+ v+ z
5	5		Corrosion	s+ w+ x+ y
VI Joint Failure				
4	3		Change in Alignment	65
3	4		Joint displacement	66
4	5		Joint Diaper	ai + 67
5	5		Joint Leaks	aa+ ab+ ac+ ad+ ae+ ag+ ah+ak
2	5		Joint Corrosion	af
5	3	VII	Deformed Pipes	aj+ ak
5	5	VIII	Leaks	leaked joints + cracked core

Stage 4 Evaluation of Predictability and Reliability of Pipe Components

Table 41 illustrates the Stage 4 calculations of the predictability index for the embedded cylinder PCCP water mains.

Table 41: Stage 4 Calculations of the Predictability Index for Embedded Cylinder PCCP Water Mains

Predictability	Reliability
I Interior Mortar Coating	
4	**5**
II Exterior Mortar Coating	
5	**5**
III Steel Cylinder	
5	**5**
IV Pre-stressed Wire	
5	**5**
V Concrete Core	
5	**5**
VI Joint Failure	
4	5

Stage 5 Evaluation of Predictability and Reliability of Pipe

Table 42 illustrates the Stage 5 calculations of the predictability index for the embedded cylinder PCCP water mains.

Table 42: Stage 5 Calculations of the Predictability Index for Embedded Cylinder PCCP Water Mains

Failure- Burst	
Predictability	Reliability
5	**5**

Stage 6 Evaluation of Predictability and Reliability of Pipe System

Table 43 illustrates the Stage 6 calculations of the predictability index for the embedded cylinder PCCP water mains.

Table 43: Stage 6 Calculations of the Predictability Index for Embedded Cylinder PCCP Water Mains

Sub- Index					**Parameter**
Predictability	Reliability	Sub- Index Description	Severity/ Occurrence	Reliability	
5	5	Condition of the pipe barrel + Joint Condition	5	5	
		High- risk Situations/ Scenarios	5	5	Proximity to major railways and roadways
					Proximity to a liquefaction area
					Proximity to a landslide prone area
					Proximity to a pipe surface damaging chemicals
					Potential exposure to corrosion
					External loading scenario
					Differential settlement
					Extreme temperature/Water quality
			5	5	Others- Serves a huge population
		Water Quality			Water pH
					Alkalinity
					Hardness
					Total dissolved salts

Sub- Index					**Parameter**
Predictability	Reliability	Sub- Index Description	Severity/ Occurrence	Reliability	
					water temperature
					turbidity
					chemicals
					others- mud found

Appendix J: Predictability Index for Lined Cylinder PCCP Water Mains

There are 6 stages for calculation of predictability index of PCCP water mains.

Stage 1: Evaluation of Severity/ Occurrence and Reliability of Data Parameters

Table 44 illustrates the Stage 1 calculations of the predictability index for the lined cylinder PCCP water mains.

Table 44: Stage 1 Calculations of the Predictability Index for Lined Cylinder PCCP Water Mains

						This is where the data is to be included by the users	**Here the Users have to justify their data by specifying their level on confidence on the data**		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
		The stage of the pipe's life where the required data is to be collected	**Explanation of the inputs that are required**				Direct Data- 5, Incomplete Data-4, Indirect Data-3, Educated Guess-2, No Data-1	Very High-5, High- 4, Medium-3, Low- 2, Very Low- 1	Very High-5, High- 4, Medium-3, Low- 2, Very Low-1
1	Lining thickness/ design thickness	Manufacturing, Installation, Operations	The ratio of the present lining thickness to the design lining thickness	Ratio	0 onwards (Ideally 1)	0.5	4	5	4
Manufacturing									

						This is where the data is to be included by the users	Here the Users have to justify their data by specifying their level on confidence on the data		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
2	Manufacturing Inspection	Manufacturing	Manufacturing Inspection is inspection for cracks in pipes before the pipes are sent for installation	Level	inspected and no cracks-2, inspected and minor cracks-1, inspected and major cracks-0, not inspected- 1	1	4	3	4
3	Curing Time/ Design Curing time	Manufacturing	the ratio of the curing time provided for the concrete against the design concrete curing time	Ratio	0 onwards (Ideally 1)	0.5	3	5	3
4	cement content/ design cement content	Manufacturing	The ratio of the observed cement content in the pipe against the design cements content. This is done by taking samples and testing	Ratio	0 onwards (Ideally 1)	1.2	3	2	3
5	Wire manufacturing	Manufacturing	Wire should not be overheated while drawing lines. Wire manufacturing inspection needs to be done	Level	1-5	4	3	4	3
6	Wire Class	Manufacturing	The Class of the wire defines the strength of the wire	Grade	I-1, II-2, III-3, IV-4	2	5	3	5

						This is where the data is to be included by the users	**Here the Users have to justify their data by specifying their level on confidence on the data**		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
7	Elastic limit/ working pressure	Manufacturing		ratio	2.25		2	3	2
8	Wire tensile strength	Manufacturing		psi	80000	6000	4	4	4
	Installation								
9	Encasement	Installation	The presence of encasement	Yes/ No	Yes-1, No- 0	1	4	3	4
10	Design Constructability	Installation	The design constructability is the level of difficulty faced by the constructing professionals for laying the pipes	Level	1-5, with 1 being the easy to construct and 5 being difficult to construct	3	4	3	4
11	Installation Inspection/ Orderly Installation	Installation	Inspection is required at various phases of the pipe's life. Installation Inspection is the inspection whether the pipes are being laid in the right order as designated.	level	Inspected and installed perfectly- 2, Inspected and not installed perfectly-1, Not inspected- 0	0	5	4	5

						This is where the data is to be included by the users	Here the Users have to justify their data by specifying their level on confidence on the data		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
12	Installation inspection for leaks and cracks	Installation	Inspection is required at various phases of the pipe's life. Installation Inspection is the inspection whether the pipes laid are not leaking	level	Inspected and installed perfectly-2, Inspected and not installed perfectly-1, Not inspected- 1	0	5	4	5
13	Post Transportation Inspection	Installation	In transportation, there are chances of rough handling which may lead to cracking of the pipes.	Level	inspected and no cracks-2, inspected and minor cracks-1, inspected and major cracks-0, not inspected- 3	1	4	3	4
14	Weld	Installation	Welding process is a very skillful process and need constant inspection for the final product	Level	inspected and properly welded-2, inspected and minor faults-1, inspected and major faults-0, not inspected- 3	2	4	1	4
15	External Coating	Installation	Presence of external coating	Yes/no -Type	Yes-1, No- 0	1	3	1	3

						This is where the data is to be included by the users	Here the Users have to justify their data by specifying their level on confidence on the data		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
16	joint fit up	Installation	The joint fittings should be inspected whether done properly	Level	Joint fitting inspected and fitted properly-2, joint fitting not inspected-1, joint fitting inspected and force fitted- 0	0	5	4	5
17	Joint coating	Installation	The presence of joint coating has to be installed	Level	Presence of joint coating- 2, presence of joint coating but not well coated-1, no joint coating-0	1	4	3	4
18	PCCP differences	Installation	There are differences in the type of PCCP used in the same network	Level			4	3	4
19	Concrete Strength/ Design Strength	Installation	Ratio of the cast pipe strength to the design strength	Ratio	0 onwards (Ideally 1)	0.75	3	3	3
20	Aggregate size/design size	Installation	Ratio of the aggregate size to the design aggregate size	Ratio	0 onwards (Ideally 1)	1.2	3	2	3

						This is where the data is to be included by the users	**Here the Users have to justify their data by specifying their level on confidence on the data**		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
21	Carbonation of concrete	Installation	Whether concrete was carbonated or not	yes/ No	Yes- 1, No- 0	1	5	4	5
22	Difference in pH	Installation	Difference in pH	level	0-5	3	4	5	4
23	Water Cement Ratio/ Design Water Cement Ratio	Installation	The ratio of the water cement ratio to the design water cement ratio	ratio	0 onwards (Ideally 1)	1.1	3	1	3
24	Hydrotest Pressure/ Design Pressure	Installation, Operations	The Ratio of the Hydrotest pressure to the design pressure of the pipe. Greater Hydrotest pressure cracks the coating	Ratio	0 onwards (Ideally 1)	0.8	3	1	3
Operations									
24	soil resistivity	Operations	The ratio of the present soil resistivity to the min soil resistivity required in soil (3000 ohm-cm)	ohm cm	0- 12000	2000	3	2	3
25	Wire Breaks	Operations	The count of wire breaks	Dia- 48" : number	Breaks>= 41-5, 21<=Breaks<40-4, 6<=breaks<20-3,<5 breaks-2, no breaks-1	4	3	4	3

						This is where the data is to be included by the users	Here the Users have to justify their data by specifying their level on confidence on the data		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
				Dia-96" : number	Breaks>= 81-5, 41<=Breaks<80-4, 11<=breaks<40-3,<10 breaks-2, no breaks-1	4	3	4	3
26	Surge Pressure/ Design Pressure	Operations	The Ratio of the observed surge pressure over the design pressure of the pipe	Ratio	0 onwards (Ideally 1)	5	4	5	4
27	Load(dead load + live load)/ Design Load	Operations	The ratio of the load acting on the pipe to the load it is designed for	Ratio	0 onwards (Ideally 1)	5	4	5	4
28	Alkali Reactivity Tested/ Design Alkali Reactivity	Operations	The Ratio of the tested alkali reactivity of the concrete against the design alkali reactivity	Ratio	0 onwards (Ideally 1)	1.3	5	4	5
29	ppm of chlorides in soil/700ppm	Operations	The ratio of the present chloride content in soil to the acceptable level of 700 ppm	Ratio	0 onwards (Ideally 1)	1.1	4	2	4

						This is where the data is to be included by the users	Here the Users have to justify their data by specifying their level on confidence on the data		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
30	Bedding Stiffness/design stiffness	Operations	The ratio of the present bedding stiffness to the designed stiffness of the bedding	Ratio	0 onwards (Ideally 1)	0.5	3	5	3
31	pipe restraint	Operations					1	3	1
32	concrete core stiffness/ spigot ring stiffness	Operations					5	2	5
33	Pipe location	Operations	Pipe in soil or whether it is outside soil	Level	Pipe completely in Soil- 2, Pipe partially in Soil-1, Pipe completely outside-0	2	3	3	3
34	Pipe Age/ Design Life of the pipe	Operations	The age of the pipe is not a direct measure	Ratio	0 onwards (Ideally 1)	4	3	5	3
35	Pipe Depth	Operations	Depth of the Pipe from surface	Ft				4	
36	Thrust Restraint	Operations		Yes-No/ Type			5	3	5
37	Soil Type	Operations					2	2	2
38	Climate- Temperature	Operations	Temperature of the Soil	F			4	3	4

						This is where the data is to be included by the users	**Here the Users have to justify their data by specifying their level on confidence on the data**		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
39	Loading Condition (Dead Load)	Operations	The Dead Load acting on the pipeline system	lbs/sq.ft			3	4	3
40	Loading Condition (Live Load)	Operations	The Live load acting on the pipeline system	lbs/sq.ft			2	5	2
41	Aggressive Water	Operations	The presence of aggressive water flow through the pipeline system	Yes-1/no-0			3	1	3
42	Soil Corrosivity	Operations	Soil corrosivity is influenced by various factors namely soil type, soil disturbance, soil pH, soil resistivity, red-ox potential, chloride content, chloride content, microbial influenced				1	3	1
43	Soil pH	Operations	The range should be 5-8 anything else could give rise to soil corrosivity	pH	0-14	4	1	2	1
44	Soil Chloride	Operations	The content of chloride in the soil. It is measured on a percentage scale	%			1	4	1

						This is where the data is to be included by the users	Here the Users have to justify their data by specifying their level on confidence on the data		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
45	Soil Sulphate	Operations	The content of sulphate in the soil. It is measured on a percentage scale	%			5	2	5
46	Soil sulfide	Operations	The content of sulfide in the soil. It is measured on a percentage scale	%			5	3	5
47	Soil Eration	Operations					3	4	3
48	Soil porosity	Operations					4	5	4
49	Groundwater Table	Operations	The level of groundwater table	Ft			2	3	2
50	Frost Penetration	Operations					4	4	4
51	Soil Moisture Content	Operations	The level of moisture content of the soil	Level	Poor Drainage Continuously wet- 2, fair drainage, generally moist-1, good drainage generally dry- 0		3	4	3
52	Water Corrosivity	Operations					1	2	1
53	Stray Currents	Operations	Presence of stray currents				5	4	5

						This is where the data is to be included by the users	**Here the Users have to justify their data by specifying their level on confidence on the data**		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
54	Soil Disturbance	Operations	Disturbed soil may lead to aeration of soil, which leads to soil corrosivity	yes/ no-level	Highly disturbed soil- 2, Slightly disturbed soil- 1, Undisturbed soil-0		3	2	3
55	Non Uniform Soil	Operations	The presence of non uniform Soil	Yes/No			4	3	4
56	Runoff Rate	Operations	The run off changes the behavior of the soil and the other surroundings with interaction with the pipe	cu.ft/sec.			2	4	2
57	Concrete Exposed to moisture/ Cl-	Operations	The % of concrete core exposed to moisture and chloride has to be below the limit of 0.10%	%	0.001		4	5	4
58	Concrete exposed to moisture without Cl-	Operations	The % of concrete core exposed to moisture without chloride has to be below the limit of 0.15%	%	0.0015		4	3	4
59	Corrosion of steel reinforcements	Operations	The observations of corrosion leads to concrete data to support failure of the pipe				3	2	3

						This is where the data is to be included by the users	**Here the Users have to justify their data by specifying their level on confidence on the data**		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
60	Crack Type	Operations	There are different types of cracks	Type	Longitudinal (Spring Line)- 5, Mixed (long+circum)-4, Longitudinal (crown/ invert)-3, Circumferential-2, No Crack- 1	4	3	4	3
61	Crack Width	Operations	The width of the crack indicates it seriousness	mm	>= 10 mm - 5, >=5mm- 4, >=1mm- 3, Hairline- 2, No cracks-1	4	3	4	3
62	Crack Density	Operations	The spacing between the cracks	mm	Crack Spacing>= 100mm -5, Crack spacing>50-4, Crack Spacing<=50-3, No cracks-1	4	3	4	3

						This is where the data is to be included by the users	Here the Users have to justify their data by specifying their level on confidence on the data		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
63	Sound Test	Operations	Hammer Tapping sound, Hollow Sound, No Sound	Type	Very Firm Tapping Sound-5, Firm Tapping Sound-4, Slightly Hollow Tapping Sound-3, Moderately Hollow Sound-2, Very Hollow Sound-1, No Sound-0	4	3	4	3
64	Pipe Geometry	Operations	Shape of the pipe is a clear indicator of the structure of the pipe		Bulge> 3% of the diameter- 5, Bulge between 2% and 3% of the diameter-4, Bulge between 1% and 2% of the diameter- 3, Bulge< 1% of the diameter- 2, No Bulge-1	4	3	4	3

						This is where the data is to be included by the users	Here the Users have to justify their data by specifying their level on confidence on the data		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
65	Alignment of the pipe	Operations	The alignment of the pipe when compared to the actual placement of the pipes	Type	Angle>22.5 or alignment>11%- 5, 6%< alignment<10%-4, angle<22.5 or alignment<5%- 3, No change-1	4	3	4	3
66	Joint Displacement	Operations	The joints can be displaced without undergoing joint misalignment	Type	Joint displaced- 1, Joint not displaced- 0		4	3	4
67	Joint diaper crack size	Operations	The diaper crack width is measured	Type	>= 10 mm - 5, >=5mm- 4, >=1mm- 3, Hairline- 2, No cracks-1	4	3	4	3
68	Delamination	Operations	The existence of delamination	Type	Yes- 2, May be-1, No-0	1	3	3	3
69	Coloration	Operations	The Color of the mortar coating is a clear indicator of the condition of the concrete layer	Type	Obvious Rust Strains-5, Moderate Rust Strains-4, Slight Rust Strains-3, No Strains-1	4	3	4	3

						This is where the data is to be included by the users	Here the Users have to justify their data by specifying their level on confidence on the data		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
70	Hollow Area	Operations	The existence of Hollow area indicates weakness in the structure	Type	Hollow area>= 6%-5, 4%<= Hollow Area<6%-4, 2%<=Hollow Area<4-3, Hollow Area<2%-2, No Hollow Area-1	4	3	4	3
71	Leaks	Operations	The volume of leak is measured to verify if it is in the acceptable range	Gallon / Min	0 onwards	5	4	5	4

Stage 2 Evaluation of Severity/ Occurrence and Reliability of Failure Paths

Table 45 illustrates the Stage 2 calculations of the predictability index for the lined cylinder PCCP water mains.

Table 45: Stage 2 Calculations of the Predictability Index for Lined Cylinder PCCP Water Mains

The Index of Severity and occurrence along with the reliability index are being derived from the influencing factor's severity, occurrence and reliability. This calculation is automatic and considers the weights specified as per the possible failure path

S/O	R	s.no	Failure Paths	Weights
5	**4**	**a**	Impact load on rigid surface- mortar cracking	Loading Conditions+ design load
4	**5**	**b**	Poor Constructability of the design=> poor construction practices=>cracked lining and coating	Construction inspection+ design constructability+ installation inspection
4	**5**	**c**	Pipe Laid out of order=> under designed or over designed=> cracks/bending	Installation + Variation in design strengths + difference in beddings
4	**5**	**d**	Rough handling of pipe(wet coat, transportation, placing in the trench) => Cracking of the coating	manufacturing inspection+ post transportation inspection
4	**4**	**e**	Uneven Mortar=> Flushing of Protective alkalinity from around the wire	manufacturing inspection+ lining thickness
4	**4**	**f**	Pipe encased throughout its circumference- dissimilarity in bedding stiffness- differential settlement circumferential cracks	Encasement+ bedding stiffness
4	**5**	**g**	Inadequate or improper curing prior to prestressing => Coating shrinkage=> exposure of wire reinforcement=> corrosion	Curing time+ installation inspection+ post transportation inspection
4	**3**	**h**	Wire breaks and Splicing=> loss of pre-stress	Wire breaks
3	**4**	**i**	Hydrotest Pressures> Design pressures/Design Surge Pressure-Coating Cracks	Hydrotest pressure+ design pressure

The Index of Severity and occurrence along with the reliability index are being derived from the influencing factor's severity, occurrence and reliability. This calculation is automatic and considers the weights specified as per the possible failure path

S/O	R	s.no	Failure Paths	Weights
2	**4**	**j**	Chlorides in Soil> 700ppm - Loss of protective environment around pre-stressed wire	Chloride in soil
2	**3**		Soil resistivity< 3000 ohm-cm => Loss of protective environment around pre-stressed wire	Soil resistivity
2	**3**	**l**	Low Quality of mortar- Wire Corrosion	Mortar quality+ water cement ratio+ cement content
2	**3**	**m**	Low density of core- wire corrosion	Mortar quality+ water cement ratio+ cement content
4	**5**	**n**	low thickness of core- wire corrosion	Mortar quality+ water cement ratio+ cement content+ thickness or core
5	**2**	**o**	low cement content- wire corrosion	Mortar quality+ water cement ratio+ cement content
5	**4**	**p**	Over Pressuring- Coating cracks- Wires exposed to water- wires corrode and break- pressure in transferred to the cylinder- core cracks- cylinder exposed to water- cylinder corrodes and fails	pressure+ design pressure+ water exposure+ corrosive soils
4	**5**	**q**	Core Under designed=> loss of pre-stress	concrete strength+ design strength
4	**4**	**r**	Overheating of wire during drawing leads => poor torsion ductility and susceptibility to hydrogen embrittlement	wire manufacturing + strength
5	**5**	**s**	Alkali Reactivity and Poor concrete strength- Low Quality Cores	Alkali reactivity + concrete strength +design strength+ core strength
2	**3**	**t**	High Water Cement ratio => excessive core creep and shrinkage	Mortar quality+ water cement ratio+ cement content
3	**3**	**u**	Too Many fine aggregates=> excessive core creep and shrinkage	aggregate size+ core strength

The Index of Severity and occurrence along with the reliability index are being derived from the influencing factor's severity, occurrence and reliability. This calculation is automatic and considers the weights specified as per the possible failure path				
S/O	**R**	**s.no**	**Failure Paths**	**Weights**
5	**4**	**v**	Inadequate or improper curing prior to prestressing => excessive core creep and shrinkage	curing time+ core strength
2	**3**	**w**	High Water Cement ratio => Coating shrinkage=> exposure of wire reinforcement=> corrosion	Mortar quality+ water cement ratio+ cement content
3	**3**	**x**	Too Many fine aggregates=> Coating shrinkage=> exposure of wire reinforcement=> corrosion	aggregate size+ core strength
5	**5**	**y**	Carbonation of concrete=>differences in pH=> increased crevice corrosion	carbonation of concrete+ pH differences
3	**4**	**z**	Variation of the PCCP cores=> Cracks	variation in PCCP core
4	**5**	**aa**	Unnoticed construction damage=> leaking joints(need field inspection)	Installation inspection
4	**5**	**ab**	Missing joint coating=> leaking joints	Joint Coating +installation inspection
4	**5**	**ac**	Cracks in joint weld=> leaking joints	welding+ installation inspection
4	**5**	**ad**	Looped gasket=> leaking joints	gasket inspection+ installation inspection
4	**5**	**ae**	Poor joint fit up=> leaking joints	Joint fit up+ installation inspection
2	**5**	**af**	Inadequate pipe restraint- mechanically restrained joints- opened of mortared joints- steel joint ring exposed to corrosion- steel joint ring corroded-steel joint expands and cracks the coating-exposes the wire	Pipe restraint + joint restraints+ corrosive soils+ core strength
4	**5**	**ag**	Mis-fit of joints/ out of roundness of the mating joints => leaking of the joints	joints fitting

The Index of Severity and occurrence along with the reliability index are being derived from the influencing factor's severity, occurrence and reliability. This calculation is automatic and considers the weights specified as per the possible failure path				
S/O	**R**	**s.no**	**Failure Paths**	**Weights**
4	**3**	**ah**	Cracking of the core at the joints=> Leaking at the joints	core cracking at joints
2	**5**	**ai**	Stiffness Discontinuity between pre-stressed core and the unstressed spigot ring => circumferential cracks in the thin part of the core at the junction of the cylinder and the spigot	stiffness discontinuity
3	**3**	**aj**	Fabrication Errors=> dented pipes	fabrication errors+ installation inspection+ design constructability
5	**3**	**ak**	Poor Welds=> defective cylinders	welding+ installation inspection

Stage 3 Evaluation of Predictability and Reliability of Distress Indicators

Table 46 illustrates the Stage 3 calculations of the predictability index for the lined cylinder PCCP water mains.

Table 46: Stage 3 Calculations of the Predictability Index for Lined Cylinder PCCP Water Mains

Predictability	**Reliability**	**S.No**	**Distress Indicators**	**Weights**
I Interior Mortar Coating				
3	5		Spalling	weathering+ corrosion
4	5		Crack	b+ d+ f+ i
4	3		Coloration	69
4	5		Corrosion	crack+ corrosive properties
II Exterior Mortar Coating				
5	5		Spalling	a+ weathering+ corrosion

Predictability	**Reliability**	**S.No**	**Distress Indicators**	**Weights**
5	5		Crack	a+ b+ c+ d+ f+ i
4	3		Coloration	69
5	5		Corrosion	crack+ corrosive properties
III Steel Cylinder				
5	5		Corrosion	
5	5		Pin hole	
5	5		Crack	
IV Pre-stressed Wire				
5	5		Loss of protective layer around wires	e+ g+ h+ j+ k+ crack+ q
5	5		Wire Corrosion	l+ m+ n+ o
5	5		Wire Breaks	g+ r+ loss of protective layer+ wire corrosion
V Concrete Core				
5	5		Delamination	s+ w+ x
5	5		Crack	s+ t+ u+ v+ z
5	5		Corrosion	s+ w+ x+ y
VI Joint Failure				
4	3		Change in Alignment	65
3	4		Joint displacement	66
4	5		Joint Diaper	ai + 67
5	5		Joint Leaks	aa+ ab+ ac+ ad+ ae+ ag+ ah+ak
2	5		Joint Corrosion	af
5	3	VII	Deformed Pipes	aj+ak

Predictability	**Reliability**	**S.No**	**Distress Indicators**	**Weights**
5	5	VIII	Leaks	leaked joints + cracked core

Stage 4 Evaluation of Predictability and Reliability of Pipe Components

Table 47 illustrates the Stage 4 calculations of the predictability index for the lined cylinder PCCP water mains.

Table 47: Stage 4 Calculations of the Predictability Index for Lined Cylinder PCCP Water Mains

Predictability	Reliability
I Interior Mortar Coating	
4	**5**
II Exterior Mortar Coating	
5	**5**
III Steel Cylinder	
5	**5**
IV Pre-stressed Wire	
5	**5**
V Concrete Core	
5	**5**
VI Joint Failure	
4	5

Stage 5 Evaluation of Predictability and Reliability of Pipe

Table 48 illustrates the Stage 5 calculations of the predictability index for the lined cylinder PCCP water mains.

Table 48: Stage 5 Calculations of the Predictability Index for Lined Cylinder PCCP Water Mains

Failure- Burst	
Predictability	Reliability
5	**5**

Stage 6 Evaluation of Predictability and Reliability of Pipe System

Table 49 illustrates the Stage 6 calculations of the predictability index for the lined cylinder PCCP water mains.

Table 49: Stage 6 Calculations of the Predictability Index for Lined Cylinder PCCP Water Mains

Sub- Index					Parameter
Predictability	Reliability	Sub- Index Description	Severity/ Occurrence	Reliability	
5	5	Condition of the pipe barrel + Joint Condition	5	5	
		High-Risk Situations/ Scenarios	5	5	Proximity to major railways and roadways
					Proximity to a liquefaction area
					Proximity to a landslide prone area
					Proximity to a pipe surface damaging chemicals
					Potential exposure to corrosion
					External loading scenario
					Differential settlement
					Extreme temperature/Water quality
			5	5	Others- Serves a huge population
		Water Quality			Water pH
					Alkalinity
					Hardness
					Total dissolved salts
					water temperature
					turbidity
					chemicals
					others- mud found

Appendix K: Stage 2 Predictability Index for PCCP water main considering 60 selected data parameters

Stage 1: Evaluation of Severity/ Occurrence and Reliability of Data Parameters

Table 50 illustrates the Stage 1 calculations of the predictability index for PCCP Water Mains considering 60 data parameters.

Table 50: Stage 1 Calculations of the Predictability Index for PCCP Water Mains considering 60 data parameters

						This is where the data is to be included by the users	**Here the Users have to justify their data by specifying their level on confidence on the data**		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
		The stage of the pipe's life where the required data is to be collected	**Explanation of the inputs that are required**				Direct Data- 5, Incomplete Data-4, Indirect Data-3, Educated Guess-2, No Data-1	Very High- 5, High- 4, Medium-3, Low- 2, Very Low- 1	Very High- 5, High- 4, Medium-3, Low- 2, Very Low- 1
1	Wire Type	Manufacturing	Wire should not be overheated while drawing lines. Wire manufacturing inspection needs to be done	Class	I to IV	4	3	4	3

2	Weld	Installation	Welding process is a very skillful process and need constant inspection for the final product	Level	inspected and properly welded-2, inspected and minor faults-1, inspected and major faults-0, not inspected- 3	2	4	1	4
3	External Coating	Installation	Presence of external coating	Yes/no-Type	Yes-1, No- 0	1	3	1	3
4	Joint coating	Installation	The presence of joint coating has to be installed	Level	Presence of joint coating-2, presence of joint coating but not well coated-1, no joint coating-0	1	4	3	4
5	PCCP differences	Installation	There are differences in the type of PCCP used in the same network	Level			4	3	4

6	Concrete Strength/ Design Strength	Installation	Ratio of the cast pipe strength to the design strength	Ratio	0 onwards (Ideally 1)	0.75	3	3	3
7	Aggregate size/design size	Installation	Ratio of the aggregate size to the design aggregate size	Ratio	0 onwards (Ideally 1)	1.2	3	2	3
8	Carbonation of concrete	Installation	Whether concrete was carbonated or not	yes/ No	Yes- 1, No- 0	1	5	4	5
9	Difference in pH	Installation	Difference in pH	level	0-5	3	4	5	4
10	Hydrotest Pressure/ Design Pressure	Installation, Operations	The Ratio of the Hydrotest pressure to the design pressure of the pipe. Greater Hydrotest pressure cracks the coating	Ratio	0 onwards (Ideally 1)	0.8	3	1	3
11	soil resistivity	Operations	The ratio of the present soil resistivity to the min soil resistivity required in soil (3000 ohm-cm)	ohm cm	0- 12000	2000	3	2	3

12	Wire Breaks	Operations	The count of wire breaks	Dia- 48" : number	Breaks>= 41-5, 21<=Breaks< 40-4, 6<=breaks<20-3,<5 breaks-2, no breaks-1	4	3	4	3
				Dia- 96" : number	Breaks>= 81-5, 41<=Breaks< 80-4, 11<=breaks<40-3,<10 breaks-2, no breaks-1				
13	Surge Pressure/ Design Pressure	Operations	The Ratio of the observed surge pressure over the design pressure of the pipe	Ratio	0 onwards (Ideally 1)	5	4	5	4
14	Load(dead load + live load)/ Design Load	Operations	The ratio of the load acting on the pipe to the load it is designed for	Ratio	0 onwards (Ideally 1)	5	4	5	4
15	Alkali Reactivity Tested/ Design Alkali Reactivity	Operations	The Ratio of the tested alkali reactivity of the concrete against the design alkali reactivity	Ratio	0 onwards (Ideally 1)	1.3	5	4	5

16	ppm of chlorides in soil/700ppm	Operations	The ratio of the present chloride content in soil to the acceptable level of 700 ppm	Ratio	0 onwards (Ideally 1)	1.1	4	2	4
17	Bedding Stiffness/design stiffness	Operations	The ratio of the present bedding stiffness to the designed stiffness of the bedding	Ratio	0 onwards (Ideally 1)	0.5	3	5	3
18	pipe restraint	Operations					1	3	1
19	concrete core stiffness/ spigot ring stiffness	Operations					5	2	5
20	Pipe location	Operations	Pipe in soil or whether it is outside soil	Level	Pipe completely in Soil- 2, Pipe partially in Soil-1, Pipe completely outside-0	2	3	3	3
21	Pipe Age/ Design Life of the pipe	Operations	The age of the pipe is not a direct measure	Ratio	0 onwards (Ideally 1)	4	3	5	3
22	Pipe Depth	Operations	Depth of the Pipe from surface	Ft				4	

23	Thrust Restraint	Operations		Yes-No/ Type			5	3	5
24	Soil Type	Operations					2	2	2
25	Aggressive Water	Operations	The presence of aggressive water flow through the pipeline system	Yes-1/no-0			3	1	3
26	Soil Corrosivity	Operations	Soil corrosivity is influenced by various factors namely soil type, soil disturbance, soil pH, soil resistivity, red-ox potential, chloride content, chloride content, microbially influenced				1	3	1
27	Soil pH	Operations	The range should be 5-8 anything else could give rise to soil corrosivity	pH	0-14	4	1	2	1
28	Water Corrosivity	Operations					1	2	1
29	Stray Currents	Operations	Presence of stray currents				5	4	5
30	Soil Disturbance	Operations	Disturbed soil may lead to aeration of soil, which leads to soil corrosivity	yes/ no-level	Highly disturbed soil-2, Slightly disturbed soil-1, Undisturbed soil-0		3	2	3

31	Non Uniform Soil	Operations	The presence of non uniform Soil	Yes/No			4	3	4
32	Runoff Rate	Operations	The run off changes the behavior of the soil and the other surroundings with interaction with the pipe	cu.ft/sec.			2	4	2
33	Corrosion of steel reinforcements	Operations	The observations of corrosion leads to concrete data to support failure of the pipe				3	2	3
34	Crack Type	Operations	There are different types of cracks	Type	Longitudinal (Spring Line)-5, Mixed (long+circum) -4, Longitudinal (crown/ invert)-3, Circumferential-2, No Crack- 1	4	3	4	3
35	Crack Width	Operations	The width of the crack indicates it seriousness	mm	>= 10 mm - 5, >=5mm- 4, >=1mm- 3, Hairline- 2, No cracks-1	4	3	4	3

36	Crack Density	Operations	The spacing between the cracks	mm	Crack Spacing>= 100mm -5, Crack spacing>50-4, Crack Spacing<=50-3, No cracks-1	4	3	4	3
37	Sound Test	Operations	Hammer Tapping sound, Hollow Sound, No Sound	Type	Very Firm Tapping Sound-5, Firm Tapping Sound-4, Slightly Hollow Tapping Sound-3, Moderately Hollow Sound-2, Very Hollow Sound-1, No Sound-0	4	3	4	3
38	Joint Displacement	Operations	The joints can be displaced without undergoing joint misalignment	Type	Joint displaced- 1, Joint not displaced-0		4	3	4
39	Joint diaper crack size	Operations	The diaper crack width is measured	Type	>= 10 mm - 5, >=5mm- 4, >=1mm- 3, Hairline- 2, No cracks-1	4	3	4	3

40	Delamination	Operations	The existence of delamination	Type	Yes- 2, May be-1, No-0	1	3	3	3
41	Coloration	Operations	The Color of the mortar coating is a clear indicator of the condition of the concrete layer	Type	Obvious Rust Strains-5, Moderate Rust Strains-4, Slight Rust Strains-3, No Strains-1	4	3	4	3
42	Hollow Area	Operations	The existence of Hollow area indicates weakness in the structure	Type	Hollow area>= 6%-5, 4%<= Hollow Area<6%-4, 2%<=Hollow Area<4-3, Hollow Area<2%-2, No Hollow Area-1	4	3	4	3
43	Leaks	Operations	The volume of leak is measured to verify if it is in the acceptable range or not	Gallon/ Min	0 onwards	5	4	5	4

Stage 2 Evaluation of Severity/ Occurrence and Reliability of Failure Paths

Table 51 illustrates the Stage 2 calculations of the predictability index for PCCP Water Mains considering 60 data parameters.

Table 51: Stage 2 Calculations of the Predictability Index for PCCP Water Mains considering 60 data parameters

<table>
<tr><th colspan="5">The Index of Severity and occurrence along with the reliability index are being derived from the influencing factor's severity, occurrence and reliability. This calculation is automatic and considers the weights specified as per the possible failure path</th></tr>
<tr><th>S/O</th><th>R</th><th>s.no</th><th>Failure Paths</th><th>Weights</th></tr>
<tr><td>5</td><td>4</td><td>a</td><td>Impact load on rigid surface- mortar cracking</td><td>Loading Conditions+ design load</td></tr>
<tr><td>4</td><td>5</td><td>b</td><td>Poor Constructability of the design=> poor construction practices=>cracked lining and coating</td><td>Construction inspection+ design constructability+ installation inspection</td></tr>
<tr><td>4</td><td>5</td><td>c</td><td>Pipe Laid out of order=> under designed or over designed=> cracks/bending</td><td>Installation + Variation in design strengths + difference in beddings</td></tr>
<tr><td>4</td><td>5</td><td>d</td><td>Rough handling of pipe(wet coat, transportation, placing in the trench) => Cracking of the coating</td><td>manufacturing inspection+ post transportation inspection</td></tr>
<tr><td>5</td><td>3</td><td>f</td><td>Pipe encased throughout its circumference- dissimilarity in bedding stiffness- differential settlement circumferential cracks</td><td>Encasement+ bedding stiffness</td></tr>
<tr><td>4</td><td>5</td><td>g</td><td>Inadequate or improper curing prior to prestressing => Coating shrinkage=> exposure of wire reinforcement=> corrosion</td><td>Curing time+ installation inspection+ post transportation inspection</td></tr>
<tr><td>4</td><td>3</td><td>h</td><td>Wire breaks and Splicing=> loss of pre-stress</td><td>Wire breaks</td></tr>
<tr><td>3</td><td>4</td><td>i</td><td>Hydrotest Pressures> Design pressures/Design Surge Pressure- Coating Cracks</td><td>Hydrotest pressure+ design pressure</td></tr>
<tr><td>2</td><td>4</td><td>j</td><td>Chlorides in Soil> 700ppm - Loss of protective environment around pre-stressed wire</td><td>Chloride in soil</td></tr>
<tr><td>2</td><td>3</td><td></td><td>Soil resistivity< 3000 ohm-cm => Loss of protective environment around pre-stressed wire</td><td>Soil resistivity</td></tr>
<tr><td>1</td><td>3</td><td>l</td><td>Low Quality of mortar- Wire Corrosion</td><td>Mortar quality+ water cement ratio+ cement content</td></tr>
</table>

1	**3**	**m**	Low density of core- wire corrosion	Mortar quality+ water cement ratio+ cement content
1	**1**	**n**	low thickness of core- wire corrosion	Mortar quality+ water cement ratio+ cement content+ thickness or core
2	**2**	**o**	low cement content- wire corrosion	Mortar quality+ water cement ratio+ cement content
1	**3**	**p**	Over Pressuring- Coating cracks- Wires exposed to water- wires corrode and break- pressure in transferred to the cylinder- core cracks- cylinder exposed to water- cylinder corrodes and fails	pressure+ design pressure+ water exposure+ corrosive soils
4	**2**	**q**	Core Under designed=> loss of pre-stress	concrete strength+ design strength
4	**3**	**r**	Overheating of wire during drawing leads => poor torsion ductility and susceptibility to hydrogen embrittlement	wire manufacturing + strength
3	**4**	**s**	Alkali Reactivity and Poor concrete strength- Low Quality Cores	Alkali reactivity + concrete strength +design strength+ core strength
1	**3**	**t**	High Water Cement ratio => excessive core creep and shrinkage	Mortar quality+ water cement ratio+ cement content
3	**3**	**u**	Too Many fine aggregates=> excessive core creep and shrinkage	aggregate size+ core strength
4	**4**	**v**	Inadequate or improper curing prior to prestressing => excessive core creep and shrinkage	curing time+ core strength
1	**3**	**w**	High Water Cement ratio => Coating shrinkage=> exposure of wire reinforcement=> corrosion	Mortar quality+ water cement ratio+ cement content
3	**3**	**x**	Too Many fine aggregates=> Coating shrinkage=> exposure of wire reinforcement=> corrosion	aggregate size+ core strength
5	**5**	**y**	Carbonation of concrete=>differences in pH=> increased crevice corrosion	carbonation of concrete+ pH differences
3	**4**	**z**	Variation of the PCCP cores=> Cracks	variation in PCCP core
4	**5**	**aa**	Unnoticed construction damage=> leaking joints(need field inspection)	Installation inspection

4	**5**	**ab**	Missing joint coating=> leaking joints	Joint Coating +installation inspection
4	**5**	**ac**	Cracks in joint weld=> leaking joints	welding+ installation inspection
4	**5**	**ad**	Looped gasket=> leaking joints	gasket inspection+ installation inspection
4	**5**	**ae**	Poor joint fit up=> leaking joints	Joint fit up+ installation inspection
2	**5**	**af**	Inadequate pipe restraint- mechanically restrained joints- opened of mortared joints- steel joint ring exposed to corrosion- steel joint ring corroded- steel joint expands and cracks the coating-exposes the wire	Pipe restraint + joint restraints+ corrosive soils+ core strength
4	**5**	**ag**	Mis-fit of joints/ out of roundness of the mating joints => leaking of the joints	joints fitting
4	**3**	**ah**	Cracking of the core at the joints=> Leaking at the joints	core cracking at joints
2	**5**	**ai**	Stiffness Discontinuity between pre-stressed core and the unstressed spigot ring => circumferential cracks in the thin part of the core at the junction of the cylinder and the spigot	stiffness discontinuity
3	**3**	**aj**	Fabrication Errors=> dented pipes	fabrication errors+ installation inspection+ design constructability
5	**3**	**ak**	Poor Welds=> defective cylinders	welding+ installation inspection

Stage 3 Evaluation of Predictability and Reliability of Distress Indicators

Table 52 illustrates the Stage 3 calculations of the predictability index for PCCP Water Mains considering 60 data parameters.

Table 52: Stage 3 Calculations of the Predictability Index for PCCP Water Mains considering 60 data parameters

Predictability	**Reliability**	**S.No**	**Distress Indicators**	**Weights**
I Interior Mortar Coating				
3	5		Spalling	weathering+ corrosion

Predictability	**Reliability**	**S.No**	**Distress Indicators**	**Weights**
4	5		Crack	b+ d+ f+ i
4	3		Coloration	69
4	5		Corrosion	crack+ corrosive properties
II Exterior Mortar Coating				
3	5		Spalling	a+ weathering+ corrosion
4	5		Crack	a+ b+ c+ d+ f+ i
4	3		Coloration	69
4	5		Corrosion	crack+ corrosive properties
III Steel Cylinder				
4	5		Corrosion	
4	5		Pin hole	
4	5		Crack	
IV Pre-stressed Wire				
4	5		Loss of protective layer around wires	e+ g+ h+ j+ k+ crack+ q
1	2		Wire Corrosion	l+ m+ n+ o
4	5		Wire Breaks	g+ r+ loss of protective layer+ wire corrosion
V Concrete Core				
2	4		Delamination	s+ w+ x
4	4		Crack	s+ t+ u+ v+ z
5	5		Corrosion	s+ w+ x+ y

Predictability	**Reliability**	**S.No**	**Distress Indicators**	**Weights**
VI Joint Failure				
4	3		Change in Alignment	65
3	4		Joint displacement	66
4	5		Joint Diaper	ai + 67
5	5		Joint Leaks	aa+ ab+ ac+ ad+ ae+ ag+ ah+ak
2	5		Joint Corrosion	af
5	3	VII	Deformed Pipes	aj+ak
5	5	VIII	Leaks	leaked joints + cracked core

Stage 4 Evaluation of Predictability and Reliability of Pipe Components

Table 53 illustrates the Stage 4 calculations of the predictability index for PCCP Water Mains considering 60 data parameters.

Table 53: Stage 4 Calculations of the Predictability Index for PCCP Water Mains considering 60 data parameters

Predictability	Reliability
I Interior Mortar Coating	
4	**5**
II Exterior Mortar Coating	
4	**5**
III Steel Cylinder	
4	**5**
IV Pre-stressed Wire	
4	**5**
V Concrete Core	
5	**5**

Predictability	Reliability
VI Joint Failure	
5	5

Stage 5 Evaluation of Predictability and Reliability of Pipe

Table 54 illustrates the Stage 5 calculations of the predictability index for PCCP Water Mains considering 60 data parameters.

Table 54: Stage 5 Calculations of the Predictability Index for PCCP Water Mains considering 60 data parameters

Failure- Burst	
Predictability	Reliability
5	**5**

Stage 6 Evaluation of Predictability and Reliability of Pipe System

Table 55 illustrates the Stage 6 calculations of the predictability index for PCCP Water Mains considering 60 data parameters.

Table 55: Stage 6 Calculations of the Predictability Index for PCCP Water Mains considering 60 data parameters

Sub- Index					**Parameter**
Predictability	Reliability	Sub- Index Description	Severity/ Occurrence	Reliability	
5	5	Condition of the pipe barrel + Joint Condition	5	5	
		High-Risk Situations/ Scenarios	5	5	Proximity to major railways and roadways
					Proximity to a liquefaction area
					Proximity to a landslide prone area
					Proximity to a pipe surface damaging chemicals
					Potential exposure to corrosion

Sub- Index					**Parameter**
Predictability	Reliability	Sub- Index Description	Severity/ Occurrence	Reliability	
					External loading scenario
					Differential settlement
					Extreme temperature/Water quality
			5	5	Others- Serves a huge population
		Water Quality			Water pH
					Alkalinity
					Hardness
					Total dissolved salts
					water temperature
					turbidity
					chemicals
					others- mud found

Appendix L: WSSC Case Study

Predictability Index

We have performed 25 case studies for various pipe sections at WSSC. The values obtained by the predictability index have been compared with those obtained from the WSSC Model.

Case 1: Pipe Contract no: 66- 2621G

Pipe Description:

The PCCP pipe in contract no 66-2621 G of the WSSC case study is a selected pipe for sample calculations. Further details of the pipe are given in Table 56.

Table 56. Pipe Description for Case Study 1: Pipe Contract 66-2621G

Diameter	**66 inch**
Type of pipe	SP-12
Concrete class	E/F/G
Wire class	II
Footage of pipe	5623 ft
Location	Ashley to Connecticut

WSSC Score:

The value of the pipe inspection priority developed by WSSC for this contract is 54 (low). This value is considerably low since the wire class is lower (Class II) and is not in any high-risk situation. The factors collected in this pipe showed no sign of risk.

Predictability Score:

The Predictability Index of this pipe had a predictability of “2 (Low)” and reliability of “5 (very high)”. This implies that the pipe is not in danger and the utility is able to detect it with adequate data.

Score Comparison: **Low & Low**

The WSSC model of this pipe contract number 66-2621 G indicates that the pipe is in low risk with a value of 54. The predictability index value ‘2’ also indicates low risk.

Case 2: Pipe Contract no: 66- 2018F

Pipe Description:

The PCCP pipe in contract no 66-2018F of the WSSC case study is a selected pipe for sample calculations. Further details of the pipe are given in Table 57.

Table 57. Pipe Description for Case Study 2: Pipe Contract 66-2018F

Diameter	**54 inch**
Type of pipe	SP-12
Concrete class	Unknown
Wire class	II
Footage of pipe	32 ft
Location	Adelphi

WSSC Score:

The value of the pipe inspection priority developed by WSSC for this contract is 18 (very low). This value is considerably very low since the wire class is lower (Class II) and is not in any high-risk situation. The factors collected in this pipe showed no sign of risk.

Predictability Score:

The Predictability Index of this pipe had a predictability of “2 (Low)” and reliability of “5 (very high)”. This implies that the pipe is not in danger and the utility is able to detect it with adequate data.

Score Comparison: **very low and low**

The WSSC model of this pipe contract number 66-2018 F indicates that the pipe is in very low risk with a value of 18. The predictability index value ‘2’ also indicates low risk. The difference is because WSSC case study mainly considers high-risk scenarios and situations. In this case, the high-risk situation/scenarios show very low signs of risk. The predictability index on the other hand includes the structural behavior of the pipe, which shows signs of low risk when compared to very low risk of WSSC model.

Case 3: Pipe Contract no: 74-2085A

Pipe Description:

The PCCP pipe in contract no 74-2085A of the WSSC case study is a selected pipe for sample calculations. Further details of the pipe are given in Table 58.

Table 58. Pipe Description for Case Study 3: Pipe Contract 74-2085A

Diameter	**60 inch**
Type of pipe	SP-12
Concrete class	A/B/C/D/E
Wire class	IV
Footage of pipe	5938 ft
Location	Central avenue pumping station to RT 202

WSSC Score:

The value of the pipe inspection priority developed by WSSC for this contract is 100 (medium). This value is considerably medium since the wire class is high (Class IV) and is in high-risk situation. The factors collected in this pipe show high risk since the pipe is located near the pumping station

Predictability Score:

The Predictability Index of this pipe had a predictability of “4 (high)” and reliability of “5 (very high)”. This implies that the pipe is in danger and the utility is able to detect it with adequate data.

Score Comparison: **medium and high**

The WSSC model of this pipe contract number 74-2085 A indicates that the pipe is in medium risk with a value of 100. The predictability index value ‘4’ indicates high risk.

Case 4: Pipe Contract no: 76- 2682D

Pipe Description:

The PCCP pipe in contract no 76-2682D of the WSSC case study is a selected pipe for sample calculations. Further details of the pipe are given in Table 59.

Table 59. Pipe Description for Case Study 4: Pipe Contract 76-2686D

Diameter	**96 inch**
Type of pipe	SP-12
Concrete class	A/B/C/D/E
Wire class	IV
Footage of pipe	1672 ft
Location	Rhode Island to Kenilworth

WSSC Score:

The value of the pipe inspection priority developed by WSSC for this contract is 154 (very high). This value is considerably very high since the wire class is high (Class IV) and is in very high-risk situation. The factors collected in this pipe show very high risk since the pipe is located near a highway. Inspection showed 12inch of mud at some places and aggressive water

Predictability Score:

The Predictability Index of this pipe had a predictability of "5(very high)" and reliability of "5 (very high)". This implies that the pipe is in danger and the utility is able to detect it with adequate data.

Score Comparison: **very high and very high**

The WSSC model of this pipe contract number 76-2682 D indicates that the pipe is in very high risk with a value of 154. The predictability index value '5' indicates very high risk.

Case 5: Pipe Contract no: 75- 2394E

Pipe Description:

The PCCP pipe in contract no 75-2394E of the WSSC case study is a selected pipe for sample calculations. Further details of the pipe are given in Table 60.

Table 60. Pipe Description for Case Study 5: Pipe Contract 75-2394E

Diameter	**54 inch**
Type of pipe	SP-12
Concrete class	Unknown
Wire class	IV
Footage of pipe	4147 ft
Location	Chevy chase lake

WSSC Score:

The value of the pipe inspection priority developed by WSSC for this contract is 80 (low). This value is considerably low (Class IV) and is in low-risk situation.

Predictability Score:

The Predictability Index of this pipe had a predictability of “4(high)” and reliability of “5 (very high)”. This implies that the pipe is in high-risk and the utility is able to detect it with adequate data. The index shows high risk since the pipe is near highway and previous inspection data indicates circumferential cracks and cracks in the steel saddle.

Score Comparison: **low and high**

The WSSC model of this pipe contract number 75-2394 E indicates that the pipe is in low risk with a value of 80. The predictability index value ‘4’ indicates high risk.

Case 6: Pipe Contract no: 66- 2018F

Pipe Description:

The PCCP pipe in contract no 66-2018F of the WSSC case study is a selected pipe for sample calculations. Further details of the pipe are given in Table 61.

Table 61. Pipe Description for Case Study 6: Pipe Contract 66-2621G

Diameter	**42 inch**
Type of pipe	SP-5
Concrete class	Unknown
Wire class	II
Footage of pipe	175 ft
Location	Adelphi

WSSC Score:

The value of the pipe inspection priority developed by WSSC for this contract is 27 (very low). This value is considerably very low since the wire class is lower (Class II) and is not in any high-risk situation. The factors collected in this pipe showed no sign of risk.

Predictability Score:

The Predictability Index of this pipe had a predictability of “2 (Low)” and reliability of “5 (very high)”. This implies that the pipe is not in danger and the utility is able to detect it with adequate data.

Score Comparison: **very low and low**

The WSSC model of this pipe contract number 66-2018 F indicates that the pipe is in very low risk with a value of 27. The predictability index value ‘2’ also indicates low risk. The difference is because WSSC case study mainly considers high-risk scenarios and situations. In this case, the high-risk situation/scenarios show very low signs of risk. The predictability index on the other hand includes the structural behavior of the pipe, which shows signs of low risk when compared to very low risk of WSSC model.

Case 7: Pipe Contract no: 76-2682D

Pipe Description:

The PCCP pipe in contract no 76-2682D of the WSSC case study is a selected pipe for sample calculations. Further details of the pipe are given in Table 62.

Table 62. Pipe Description for Case Study 7: Pipe Contract 76-2682D

Diameter	**96 inch**
Type of pipe	SP-12
Concrete class	A/B/C/D/E
Wire class	IV
Footage of pipe	8443 ft
Location	Rhode Island to Kenilworth

WSSC Score:

The value of the pipe inspection priority developed by WSSC for this contract is 143 (high). This value is considerably high since the wire class is high (Class IV) and is in high-risk situation. The factors collected in this pipe show high risk since the pipe is located near a highway.

Predictability Score:

The Predictability Index of this pipe had a predictability of "4 (high)" and reliability of "5 (very high)". This implies that the pipe is in danger and the utility is able to detect it with adequate data.

Score Comparison: **high and high**

The WSSC model of this pipe contract number 76-2682 D indicates that the pipe is in high risk with a value of 143. The predictability index value '4' indicates high risk.

Case 8: Pipe Contract no: 68-3346E

Pipe Description:

The PCCP pipe in contract no 68-3346E of the WSSC case study is a selected pipe for sample calculations. Further details of the pipe are given in Table 63.

Table 63. Pipe Description for Case Study 8: Pipe Contract 68-3346E

Diameter	**48 inch**
Type of pipe	SP-12
Concrete class	B/C/E
Wire class	II
Footage of pipe	410 ft
Location	Avery to Georgia

WSSC Score:

The value of the pipe inspection priority developed by WSSC for this contract is 26 (very low). This value is considerably very low since the wire class is low (Class II) and is not in high-risk situation.

Predictability Score:

The Predictability Index of this pipe had a predictability of “3 (Medium)” and reliability of “5 (very high)”. This implies that the pipe is medium risk and the utility is not able to detect it with adequate data.

Score Comparison: **very low and medium**

The WSSC model of this pipe contract number 68-3346E indicates that the pipe is in very low risk with a value of 26. The predictability index value ‘3’ also indicates medium risk. The difference is because WSSC case study mainly considers high-risk scenarios and situations. In this case, the high-risk situation/scenarios show signs of risk. This is because a pipe in this contract has failed in the past. The pipe is in a hilly area with a not clear right of way. The predictability index on the other hand includes the structural behavior of the pipe, which shows signs of low risk when compared to very low risk of WSSC model

Case 9: Pipe Contract no: 1449

Pipe Description:

The PCCP pipe in contract no 1449 of the WSSC case study is a selected pipe for sample calculations. Further details of the pipe are given in Table 64.

Table 64. Pipe Description for Case Study 9: Pipe Contract 1449

Diameter	**36 inch**
Type of pipe	SP-5
Concrete class	Unknown
Wire class	unknown
Footage of pipe	9000 ft
Location	Rocky gorge station to Patuxent plant

WSSC Score:

The value of the pipe inspection priority developed by WSSC for this contract is 52 (low). This value is considerably low and is not in high-risk situation.

Predictability Score:

The Predictability Index of this pipe had a predictability of “2 (low)” and reliability of “3 (Indirect data)”. This implies that the pipe is not in danger but the utility is not able to detect because of inadequate data.

Score Comparison: **low and low**

The WSSC model of this pipe contract number 1449 indicates that the pipe is in low risk with a value of 52. The predictability index value ‘2’ indicates low risk. However predictability index indicates inadequate data.

Case 10: Pipe Contract no: 68-3346C

Pipe Description:

The PCCP pipe in contract no 68-3346C of the WSSC case study is a selected pipe for sample calculations. Further details of the pipe are given in Table 65.

Table 65. Pipe Description for Case Study 10: Pipe Contract 68-3346C

Diameter	**48 inch**
Type of pipe	SP-12
Concrete class	A/B/C/D
Wire class	II
Footage of pipe	16447 ft
Location	Route 355 to Avery

WSSC Score:

The value of the pipe inspection priority developed by WSSC for this contract is 78 (low). This value is considerably low and is not in high-risk situation.

Predictability Score:

The Predictability Index of this pipe had a predictability of “2 (low)” and reliability of “5 (very high)”. This implies that the pipe is not in danger and the utility is able to detect it with adequate data.

Score Comparison: **low and low**

The WSSC model of this pipe contract number 68-3346C indicates that the pipe is in low risk with a value of 78. The predictability index value ‘2’ indicates low risk.

Case 11: Pipe Contract no: 70- 4479B

Pipe Description:

The PCCP pipe in contract no 70-4479B of the WSSC case study is a selected pipe for sample calculations. Further details of the pipe are given in Table 66.

Table 66. Pipe Description for Case Study 11: Pipe Contract 70-4479B

Diameter	**54 inch**
Type of pipe	SP-12
Concrete class	Unknown
Wire class	IV
Footage of pipe	40 ft
Location	Along I-270 Gaithersburg

WSSC Score:

The value of the pipe inspection priority developed by WSSC for this contract is 80 (low). This value is considerably low and is not in high-risk situation.

Predictability Score:

The Predictability Index of this pipe had a predictability of "5 (very high)" and reliability of "5 (very high)". This implies that the pipe is in danger and the utility is able to detect it with adequate data. The pipe show very high risk since it is located near a highway, high water and muck at invert.

Score Comparison: **low and very high**

The WSSC model of this pipe contract number 70-4479B indicates that the pipe is in low risk with a value of 80. The predictability index value '5' indicates very high risk.

Case 12: Pipe Contract no: 74-2189A

Pipe Description:

The PCCP pipe in contract no 74-2189A of the WSSC case study is a selected pipe for sample calculations. Further details of the pipe are given in Table 67.

Table 67. Pipe Description for Case Study 12: Pipe Contract 74-2189A

Diameter	**36 inch**
Type of pipe	SP-5
Concrete class	Unknown
Wire class	IV
Footage of pipe	215 ft
Location	Allen town road at Leon street

WSSC Score:

The value of the pipe inspection priority developed by WSSC for this contract is 130 (high). This value is considerably high and is not in a high-risk situation.

Predictability Score:

The Predictability Index of this pipe had a predictability of “4 (high)” and reliability of “5 (very high)”. This implies that the pipe is in danger and the utility is able to detect it with adequate data.

Score Comparison: **high and high**

The WSSC model of this pipe contract number 74-2189A indicates that the pipe is in high risk with a value of 130. The predictability index value ‘4’ indicates high risk.

Case 13: Pipe Contract no: 70-4479A

Pipe Description:

The PCCP pipe in contract no 70-4479A of the WSSC case study is a selected pipe for sample calculations. Further details of the pipe are given in Table 68.

Table 68. Pipe Description for Case Study 13: Pipe Contract 70-4479A

Diameter	**36 inch**
Type of pipe	SP-5
Concrete class	A/B
Wire class	IV
Footage of pipe	5093 ft
Location	Along I-270 Gaithersburg

WSSC Score:

The value of the pipe inspection priority developed by WSSC for this contract is 182 (very high). This value is considerably very high since the class of pipe is high (class IV) and is in a high-risk situation. In addition, the pipe is located near a highway and a pipe in the same contract encountered a break in the past.

Predictability Score:

The Predictability Index of this pipe had a predictability of “5(very high)” and reliability of “5 (very high)”. This implies that the pipe is in danger and the utility is able to detect it with adequate data.

Score Comparison: **very high and very high**

The WSSC model of this pipe contract number 70-4479A indicates that the pipe is in high risk with a value of 182. The predictability index value ‘5’ indicates very high risk.

Case 14: Pipe Contract no: 73-5648B

Pipe Description:

The PCCP pipe in contract no 73-5648B of the WSSC case study is a selected pipe for sample calculations. Further details of the pipe are given in Table 69.

Table 69. Pipe Description for Case Study 14: Pipe Contract 73-5648B

Diameter	**42 inch**
Type of pipe	SP-5
Concrete class	A/B/C/D/E
Wire class	IV
Footage of pipe	6325 ft
Location	Henson creek-rosecroft to temple hill

WSSC Score:

The value of the pipe inspection priority developed by WSSC for this contract is 198 (very high). This value is considerably very high since the class of pipe is high (class IV) and is not in a high-risk situation. However, couple of pipes in the same contract has failed in the past.

Predictability Score:

The Predictability Index of this pipe had a predictability of “5(very high)” and reliability of “5 (very high)”. This implies that the pipe is in danger and the utility is able to detect it with adequate data.

Score Comparison: **very high and very high**

The WSSC model of this pipe contract number 73-5648B indicates that the pipe is in high risk with a value of 198. The predictability index value '5' indicates very high risk.

Case 15: Pipe Contract no: 4750

Pipe Description:

The PCCP pipe in contract no 4750 of the WSSC case study is a selected pipe for sample calculations. Further details of the pipe are given in Table 70.

Table 70. Pipe Description for Case Study 15: Pipe Contract 4750

Diameter	**36 inch**
Type of pipe	SP-5
Concrete class	A/B
Wire class	II
Footage of pipe	25207 ft
Location	Along dower house beltway to Woodward road

WSSC Score:

The value of the pipe inspection priority developed by WSSC for this contract is 111 (high). This value is considerably high and is in a high-risk situation.

Predictability Score:

The Predictability Index of this pipe had a predictability of "4(high)" and reliability of "5 (very high)". This implies that the pipe is in danger and the utility is able to detect it with adequate data. The pipe shows a high risk because it is located along a beltway.

Score Comparison: **high and high**

The WSSC model of this pipe contract number 4750 indicates that the pipe is in high risk with a value of 111. The predictability index value ‘4’ indicates high risk.

Case 16: Pipe Contract no: 68-3347A

Pipe Description:

The PCCP pipe in contract no 68-3347A of the WSSC case study is a selected pipe for sample calculations. Further details of the pipe are given in Table 71.

Table 71. Pipe Description for Case Study 1: Pipe Contract 66-2621G

Diameter	**42 inch**
Type of pipe	SP-12
Concrete class	D
Wire class	unknown
Footage of pipe	452 ft
Location	College avenue to norwood

WSSC Score:

The value of the pipe inspection priority developed by WSSC for this contract is 8 (very low). This value is considerably very low and is in not a high-risk situation.

Predictability Score:

The Predictability Index of this pipe had a predictability of “3(medium)” and reliability of “4 (high)”. This implies that the pipe is not in danger and the utility is not able to detect it because of inadequate data.

Score Comparison: **very low and medium**

The WSSC model of this pipe contract number 68-3347A indicates that the pipe is in a very low risk with a value of 8. The predictability index value ‘3’ indicates medium risk.

Case 17: Pipe Contract no: 4620

Pipe Description:

The PCCP pipe in contract no 4620 of the WSSC case study is a selected pipe for sample calculations. Further details of the pipe are given in Table 72.

Table 72. Pipe Description for Case Study 17: Pipe Contract 4620

Diameter	**48 inch**
Type of pipe	SP-12
Concrete class	D
Wire class	Unknown
Footage of pipe	905 ft
Location	Bel pre road to norwood road

WSSC Score:

The value of the pipe inspection priority developed by WSSC for this contract is 26 (very low). This value is considerably very low and is in not a high-risk situation.

Predictability Score:

The Predictability Index of this pipe had a predictability of “2(low)” and reliability of “4 (high)”. This implies that the pipe is not in danger and the utility has incomplete data.

Score Comparison: **very low and low**

The WSSC model of this pipe contract number 4620 indicates that the pipe is in a very low risk with a value of 26. The predictability index value ‘2’ indicates low risk.

Case 18: Pipe Contract no: 3901

Pipe Description:

The PCCP pipe in contract no 3901 of the WSSC case study is a selected pipe for sample calculations. Further details of the pipe are given in Table 73.

Table 73.Pipe Description for Case Study 18: Pipe Contract 3901

Diameter	**60 inch**
Type of pipe	SP-12
Concrete class	Unknown
Wire class	Unknown
Footage of pipe	12 ft
Location	Potomac water filtration plant

WSSC Score:

The value of the pipe inspection priority developed by WSSC for this contract is 65 (low). This value is considerably low and is in not a high-risk situation.

Predictability Score:

The Predictability Index of this pipe had a predictability of “5(very high)” and reliability of “5(very high)”. This implies that the pipe is in danger and the utility is able to detect it because of adequate data. The pipe is considered as very high risk because it is located in a power filtration plant.

Score Comparison: **low and very high**

The WSSC model of this pipe contract number 3901 indicates that the pipe is in a low risk with a value of 65. The predictability index value ‘5’ indicates very high risk because of its location.

Case 19: Pipe Contract no: 80-4665A

Pipe Description:

The PCCP pipe in contract no 80-4665A of the WSSC case study is a selected pipe for sample calculations. Further details of the pipe are given in Table 74.

Table 74. Pipe Description for Case Study 19: Pipe Contract 80-4665A

Diameter	**36 inch**
Type of pipe	SP-5
Concrete class	unknown
Wire class	IV
Footage of pipe	150 ft
Location	German town drive at waters landing drive

WSSC Score:

The value of the pipe inspection priority developed by WSSC for this contract is 72 (low). This value is considerably low and is in not a high-risk situation.

Predictability Score:

The Predictability Index of this pipe had a predictability of “4(high)” and reliability of “5(very high)”. This implies that the pipe is in danger and the utility is able to detect it because of adequate data.

Score Comparison: **low and high**

The WSSC model of this pipe contract number 80-4665A indicates that the pipe is in a low risk with a value of 72. The predictability index value ‘4’ indicates high risk

Case 20: Pipe Contract no: 76-6962A

Pipe Description:

The PCCP pipe in contract no 76-6962A of the WSSC case study is a selected pipe for sample calculations. Further details of the pipe are given in Table 75.

Table 75. Pipe Description for Case Study 20: Pipe Contract 76-6962G

Diameter	**48 inch**
Type of pipe	SP-12
Concrete class	Unknown
Wire class	IV
Footage of pipe	2285 ft
Location	Shady grove service and inspection yard

WSSC Score:

The value of the pipe inspection priority developed by WSSC for this contract is 91 (medium). This value is considerably medium and is in not a high-risk situation.

Predictability Score:

The Predictability Index of this pipe had a predictability of “4(high)” and reliability of “5(very high)”. This implies that the pipe is in danger and the utility is able to detect it because of adequate data.

Score Comparison: **medium and high**

The WSSC model of this pipe contract number 76-6962A indicates that the pipe is in a low risk with a value of 72. The predictability index value '4' indicates high risk.

Case 21: Pipe Contract no: 74-2085A

Pipe Description:

The PCCP pipe in contract no 74-2085A of the WSSC case study is a selected pipe for sample calculations. Further details of the pipe are given in Table 76.

Table 76. Pipe Description for Case Study 21: Pipe Contract 74-2085A

Diameter	**36 inch**
Type of pipe	SP-5
Concrete class	unknown
Wire class	IV
Footage of pipe	35 ft
Location	Central avenue pumping station to route 202

WSSC Score:

The value of the pipe inspection priority developed by WSSC for this contract is 90 (medium). This value is considerably medium and is in a high-risk situation.

Predictability Score:

The Predictability Index of this pipe had a predictability of "5(very high)" and reliability of "5(very high)". This implies that the pipe is in danger and the utility is able to detect it because of adequate data.

Score Comparison: **medium and very high**

The WSSC model of this pipe contract number 74-2085A indicates that the pipe is in a medium risk with a value of 90. The predictability index value '5' indicates very high risk because it is located at a pumping station.

Case 22: Pipe Contract no: 71-4809A

Pipe Description:

The PCCP pipe in contract no 71-4809A of the WSSC case study is a selected pipe for sample calculations. Further details of the pipe are given in Table 77.

Table 77. Pipe Description for Case Study 22: Pipe Contract 71-4809A

Diameter	**36 inch**
Type of pipe	SP-5
Concrete class	A/B
Wire class	IV
Footage of pipe	3490 ft
Location	Montgomery village to Goshen

WSSC Score:

The value of the pipe inspection priority developed by WSSC for this contract is 130 (high). This value is considerably high since the pipe class is high (class IV) and is not in a high-risk situation.

Predictability Score:

The Predictability Index of this pipe had a predictability of “4(high)” and reliability of “5(very high)”. This implies that the pipe is in danger and the utility is able to detect it because of adequate data.

Score Comparison: **high and high**

The WSSC model of this pipe contract number 71-4809A indicates that the pipe is in a high risk with a value of 130. The predictability index value ‘4’ indicates high risk.

Case 23: Pipe Contract no: 75-2344E

Pipe Description:

The PCCP pipe in contract no 75-2344E of the WSSC case study is a selected pipe for sample calculations. Further details of the pipe are given in Table 78.

Table 78. Pipe Description for Case Study 23: Pipe Contract 75-2344E

Diameter	**60 inch**
Type of pipe	SP-12
Concrete class	Unknown
Wire class	III
Footage of pipe	229 ft
Location	Route 495

WSSC Score:

The value of the pipe inspection priority developed by WSSC for this contract is 110 (medium). This value is high and is in a high-risk situation because it is located near a highway.

Predictability Score:

The Predictability Index of this pipe had a predictability of “5(very high)” and reliability of “5(very high)”. This implies that the pipe is in danger and the utility is able to detect it because of adequate data.

Score Comparison: **high and very high**

The WSSC model of this pipe contract number 75-2344E indicates that the pipe is in a high risk with a value of 110. The predictability index value ‘5’ indicates very high risk because it is located near a highway.

Case 24: Pipe Contract no: 4749

Pipe Description:

The PCCP pipe in contract no 4749 of the WSSC case study is a selected pipe for sample calculations. Further details of the pipe are given in Table 79.

Table 79. Pipe Description for Case Study 24: Pipe Contract 4749

Diameter	**36 inch**
Type of pipe	SP-5
Concrete class	C/D
Wire class	II
Footage of pipe	11535 ft
Location	Along beltway Henson CR to Virginia la

WSSC Score:

The value of the pipe inspection priority developed by WSSC for this contract is 224 (very high). This value is considerably very high and is in a high-risk situation because of its location along a beltway.

Predictability Score:

The Predictability Index of this pipe had a predictability of “5(very high)” and reliability of “5(very high)”. This implies that the pipe is in danger and the utility is able to detect it because of adequate data.

Score Comparison: **very high and very high**

The WSSC model of this pipe contract number 4749 indicates that the pipe is in a very high risk with a value of 224. The predictability index value ‘5’ indicates very high risk because it is located at a pumping station. The pipe is considered as very high risk because of its location along the beltway.

Case 25: Pipe Contract no: 72-5359A

Pipe Description:

The PCCP pipe in contract no 72-5359A of the WSSC case study is a selected pipe for sample calculations. Further details of the pipe are given in Table 80.

Table 80. Pipe Description for Case Study 25: Pipe Contract 72-5359A

Diameter	**36 inch**
Type of pipe	SP-5
Concrete class	unknown
Wire class	IV
Footage of pipe	376 ft
Location	Along beltway Penn to Ritchie Marlboro

WSSC Score:

The value of the pipe inspection priority developed by WSSC for this contract is 130 (high). This value is considerably high and is in a high-risk situation.

Predictability Score:

The Predictability Index of this pipe had a predictability of “5(very high)” and reliability of “5(very high)”. This implies that the pipe is in danger and the utility is able to detect it because of adequate data.

Score Comparison: **high and very high**

The WSSC model of this pipe contract number 72-5359A indicates that the pipe is in a high risk with a value of 130. The predictability index value ‘5’ indicates very high risk because it is located along a beltway.

Appendix M: Condition Assessability Index for Internal Mortar Coating Failure

Table 81 illustrates the Calculations of the Condition Assessability Index for Internal Mortar Coating Failure of PCCP Water Mains.

Table 81: Calculations of the Condition Assessability Index for Internal Mortar Coating Failure of PCCP Water Mains

Condition Assessability Index of Internal Mortar Coating								
Influencing Factors	**Explanation for factors**	**Unit**	**Range**	**Associated Technology**	Detectable	Cost	Condition Assessability Index	
	Explanation of the inputs that are required						Performance	Economic Analysis
Manufacturing Inspection	Manufacturing Inspection is inspection for cracks in pipes before the pipes are sent for installation	Level	inspected and no cracks-2, inspected and minor cracks-1, inspected and major cracks-0, not inspected- 1	Inspection/ Manual	Yes	Low	**4**	**3**
Curing Time/ Design Curing time	the ratio of the curing time provided for the concrete against the design concrete curing time	Ratio	0 onwards (Ideally 1)	Inspection/ Manual	Yes	Low		
Design Constructability	The design constructability is the level of difficulty faced by the constructing professionals for laying the pipes	Level	1-5, with 1 being the easy to construct and 5 being difficult to construct	Inspection/ Manual	Yes	Low		

Condition Assessability Index of Internal Mortar Coating

Influencing Factors	**Explanation for factors**	**Unit**	**Range**	**Associated Technology**	Detectable	Cost	Condition Assessability Index	
Installation Inspection/ Orderly Installation	Inspection is required at various phases of the pipe's life. Installation Inspection is the inspection whether the pipes are being laid in the right order as designated.	level	Inspected and installed perfectly- 2, Inspected and not installed perfectly-1, Not inspected- 0	Inspection/ Manual	Yes	Low		
Installation inspection for leaks and cracks	Inspection is required at various phases of the pipe's life. Installation Inspection is the inspection whether the pipes laid are not leaking	level	Inspected and installed perfectly- 2, Inspected and not installed perfectly-1, Not inspected- 1	Inspection/ Manual	Yes	Low		
Post Transportation Inspection	In transportation, there are chances of rough handling which may lead to cracking of the pipes.	Level	inspected and no cracks-2, inspected and minor cracks-1, inspected and major cracks-0, not inspected- 2	Inspection/ Manual	Yes	Low		
PCCP differences	There are differences in the type of PCCP used in the same network	Level		Inspection/ Manual	Yes	Low		
Concrete Strength/ Design Strength	Ratio of the cast pipe strength to the design strength	Ratio	0 onwards (Ideally 1)	Lab Test	Yes	Moderate		
Aggregate size/design size	Ratio of the aggregate size to the design aggregate size	Ratio	0 onwards (Ideally 1)	Inspection/ Manual	Yes	Low		

Condition Assessability Index of Internal Mortar Coating

Influencing Factors	**Explanation for factors**	**Unit**	**Range**	**Associated Technology**	Detectable	Cost	Condition Assessability Index	
Hydrotest Pressure/ Design Pressure	The Ratio of the Hydrotest pressure to the design pressure of the pipe. Greater Hydrotest pressure cracks the coating	Ratio	0 onwards (Ideally 1)	Field Test	Yes	High		
Wire Breaks	The count of wire breaks	Dia- 48" : number	Breaks>= 41-5, 21<=Breaks<40-4, 6<=breaks<20-3,<5 breaks-2, no breaks-1		Yes	Moderate		
		Dia- 96" : number	Breaks>= 81-5, 41<=Breaks<80-4, 11<=breaks<40-3,<10 breaks-2, no breaks-1	Field Test	Yes	Moderate		
Surge Pressure/ Design Pressure	The Ratio of the observed surge pressure over the design pressure of the pipe	Ratio	0 onwards (Ideally 1)	Field Test	Approximate	High		
Alkali Reactivity Tested/ Design Alkali Reactivity	The Ratio of the tested alkali reactivity of the concrete against the design alkali reactivity	Ratio	0 onwards (Ideally 1)	Field Test	Yes	Moderate		
ppm of chlorides in soil/700ppm	The ratio of the present chloride content in soil to the acceptable level of 700 ppm	Ratio	0 onwards (Ideally 1)	Field Test	Yes	Moderate		

Condition Assessability Index of Internal Mortar Coating

Influencing Factors	**Explanation for factors**	**Unit**	**Range**	**Associated Technology**	Detectable	Cost	Condition Assessability Index	
Pipe Geometry	Shape of the pipe is a clear indicator of the structure of the pipe		Bulge> 3% of the diameter- 5, Bulge between 2% and 3% of the diameter-4, Bulge between 1% and 2% of the diameter- 3, Bulge< 1% of the diameter- 2, No Bulge-1	Inspection/ Manual	Yes	Low		
Joint Displacement	The joints can be displaced without undergoing joint misalignment	Type	Joint displaced- 1, Joint not displaced-0	Inspection/ Manual	Yes	Low		

Appendix N: Condition Assessability Index for External Mortar Coating Failure

Table 82 illustrates the Calculations of the Condition Assessability Index for External Mortar Coating Failure of PCCP Water Mains.

Table 82: Calculations of the Condition Assessability Index for External Mortar Coating Failure of PCCP Water Mains

Influencing Factors	**Explanation for factors**	**Unit**	**Range**	**Associated Technology**	Detectable	Cost	Condition Assessability Index	
	Explanation of the inputs that are required						Performance	Economic Analysis
Manufacturing Inspection	Manufacturing Inspection is inspection for cracks in pipes before the pipes are sent for installation	Level	inspected and no cracks-2, inspected and minor cracks-1, inspected and major cracks-0, not inspected- 1	Inspection/ Manual	Yes	Low	**4**	**3**
cement content/ design cement content	The ratio of the observed cement content in the pipe against the design cement content. This is done by taking samples and testing	Ratio	0 onwards (Ideally 1)	Lab Test	Yes	Moderate		
Encasement	The presence of encasement	Yes/No	Yes-1, No- 0	Inspection/ Manual	Yes	Low		
Design Constructability	The design constructability is the level of difficulty faced by the constructing professionals for laying the pipes	Level	1-5, with 1 being the easy to construct and 5 being difficult to construct	Inspection/ Manual	Yes	Low		

Influencing Factors	**Explanation for factors**	**Unit**	**Range**	**Associated Technology**	Detectable	Cost	Condition Assessability Index	
Installation Inspection/ Orderly Installation	Inspection is required at various phases of the pipe's life. Installation Inspection is the inspection whether the pipes are being laid in the right order as designated.	level	Inspected and installed perfectly- 2, Inspected and not installed perfectly-1, Not inspected- 0	Inspection/ Manual	Yes	Low		
Installation inspection for leaks and cracks	Inspection is required at various phases of the pipe's life. Installation Inspection is the inspection whether the pipes laid are not leaking	level	Inspected and installed perfectly- 2, Inspected and not installed perfectly-1, Not inspected- 1	Inspection/ Manual	Yes	Low		
Post Transportation Inspection	In transportation, there are chances of rough handling which may lead to cracking of the pipes.	Level	inspected and no cracks-2, inspected and minor cracks-1, inspected and major cracks-0, not inspected- 2	Inspection/ Manual	Yes	Low		
Joint coating	The presence of joint coating has to be installed	Level	Presence of joint coating- 2, presence of joint coating but not well coated-1, no joint coating-0	Inspection/ Manual	Yes	Low		
PCCP differences	There are differences in the type of PCCP used in the same network	Level		Inspection/ Manual	Yes	Low		
Concrete Strength/ Design Strength	Ratio of the cast pipe strength to the design strength	Ratio	0 onwards (Ideally 1)	Lab Test	Yes	Moderate		

Influencing Factors	**Explanation for factors**	**Unit**	**Range**	**Associated Technology**	Detectable	Cost	Condition Assessability Index	
Water Cement Ratio/ Design Water Cement Ratio	The ratio of the water cement ratio to the design water cement ratio	ratio	0 onwards (Ideally 1)	Lab Test	Yes	Moderate		
Hydrotest Pressure/ Design Pressure	The Ratio of the Hydrotest pressure to the design pressure of the pipe. Greater Hydrotest pressure cracks the coating	Ratio	0 onwards (Ideally 1)	Field Test	Yes	High		
Surge Pressure/ Design Pressure	The Ratio of the observed surge pressure over the design pressure of the pipe	Ratio	0 onwards (Ideally 1)	Field Test	Approximate	High		
Load(dead load + live load)/ Design Load	The ratio of the load acting on the pipe to the load it is designed for	Ratio	0 onwards (Ideally 1)	Field Test	Yes	High		
Alkali Reactivity Tested/ Design Alkali Reactivity	The Ratio of the tested alkali reactivity of the concrete against the design alkali reactivity	Ratio	0 onwards (Ideally 1)	Field Test	Yes	Moderate		
ppm of chlorides in soil/700ppm	The ratio of the present chloride content in soil to the acceptable level of 700 ppm	Ratio	0 onwards (Ideally 1)	Field Test	Yes	Moderate		
Bedding Stiffness/design stiffness	The ratio of the present bedding stiffness to the designed stiffness of the bedding	Ratio	0 onwards (Ideally 1)	Field Test	Yes	Moderate		
concrete core stiffness/ spigot ring stiffness				Field Test	Yes	High		

Influencing Factors	**Explanation for factors**	**Unit**	**Range**	**Associated Technology**	Detectable	Cost	Condition Assessability Index	
Joint Displacement	The joints can be displaced without undergoing joint misalignment	Type	Joint displaced- 1, Joint not displaced-0	Inspection/ Manual	Yes	Moderate		
Coloration	The Color of the mortar coating is a clear indicator of the condition of the concrete layer	Type	Obvious Rust Strains-5, Moderate Rust Strains-4, Slight Rust Strains-3, No Strains-1	Field Test	Yes	High		

Appendix O: Condition Assessability Index for Pre-stressed Wire Failure

Table 81 illustrates the Calculations of the Condition Assessability Index for Pre-stressed Wire Failure of PCCP Water Mains.

Table 83: Calculations of the Condition Assessability Index for Pre-stressed Wire Failure of PCCP Water Mains

Influencing Factors	**Explanation for factors**	**Unit**	**Range**	**Associated Technology**	Detectable	Cost	Condition Assessability Index	
	Explanation of the inputs that are required						Performance	Economic Analysis
Lining thickness/ design thickness	The ratio of the present lining thickness to the design lining thickness	Ratio	0 onwards (Ideally 1)	Field Test	Yes	Low	**3**	**3**
Manufacturing Inspection	Manufacturing Inspection is inspection for cracks in pipes before the pipes are sent for installation	Level	inspected and no cracks-2, inspected and minor cracks-1, inspected and major cracks-0, not inspected- 1	Inspection/ Manual	Yes	Moderate		
Curing Time/ Design Curing time	the ratio of the curing time provided for the concrete against the design concrete curing time	Ratio	0 onwards (Ideally 1)	Inspection/ Manual	Yes	Low		
cement content/ design cement content	The ratio of the observed cement content in the pipe against the design cements content. This is done by taking samples and testing	Ratio	0 onwards (Ideally 1)	Lab Test	Yes	Moderate		

Influencing Factors	**Explanation for factors**	**Unit**	**Range**	**Associated Technology**	Detectable	Cost	Condition Assessability Index	
Wire manufacturing	Wire should not be overheated while drawing lines. Wire manufacturing inspection needs to be done	Level	1-5	Inspection/ Manual	Yes	Low		
Wire tensile strength		psi	80000	Lab Test	Yes	Moderate		
Encasement	The presence of encasement	Yes/No	Yes-1, No- 0	Inspection/ Manual	Yes	Low		
Design Constructability	The design constructability is the level of difficulty faced by the constructing professionals for laying the pipes	Level	1-5, with 1 being the easy to construct and 5 being difficult to construct	Inspection/ Manual	Yes	Low		
Installation Inspection/ Orderly Installation	Inspection is required at various phases of the pipe's life. Installation Inspection is the inspection whether the pipes are being laid in the right order as designated.	level	Inspected and installed perfectly- 2, Inspected and not installed perfectly-1, Not inspected- 0	Inspection/ Manual	Yes	Low		
Post Transportation Inspection	In transportation, there are chances of rough handling which may lead to cracking of the pipes.	Level	inspected and no cracks-2, inspected and minor cracks-1, inspected and major cracks-0, not inspected- 2	Inspection/ Manual	Yes	Low		
Concrete Strength/ Design Strength	Ratio of the cast pipe strength to the design strength	Ratio	0 onwards (Ideally 1)	Lab Test	Yes	Moderate		

Influencing Factors	**Explanation for factors**	**Unit**	**Range**	**Associated Technology**	Detectable	Cost	Condition Assessability Index	
Water Cement Ratio/ Design Water Cement Ratio	The ratio of the water cement ratio to the design water cement ratio	ratio	0 onwards (Ideally 1)	Lab Test	Yes	Moderate		
Hydrotest Pressure/ Design Pressure	The Ratio of the Hydrotest pressure to the design pressure of the pipe. Greater Hydrotest pressure cracks the coating	Ratio	0 onwards (Ideally 1)	Field Test	Approximate	High		
soil resistivity	The ratio of the present soil resistivity to the min soil resistivity required in soil (3000 ohm-cm)	ohm cm	0- 12000	Field Test	Yes	Moderate		
Wire Breaks	The count of wire breaks	Dia- 48" : number	Breaks>= 41-5, 21<=Breaks<40-4, 6<=breaks<20-3,<5 breaks-2, no breaks-1		Yes	Moderate		
		Dia- 96" : number	Breaks>= 81-5, 41<=Breaks<80-4, 11<=breaks<40-3,<10 breaks-2, no breaks-1	Field Test	Yes	Moderate		
Surge Pressure/ Design Pressure	The Ratio of the observed surge pressure over the design pressure of the pipe	Ratio	0 onwards (Ideally 1)	Field Test	Yes	High		
Load(dead load + live load)/ Design Load	The ratio of the load acting on the pipe to the load it is designed for	Ratio	0 onwards (Ideally 1)	Field Test	Approximate	High		

Influencing Factors	**Explanation for factors**	**Unit**	**Range**	**Associated Technology**	Detectable	Cost	Condition Assessability Index	
ppm of chlorides in soil/700ppm	The ratio of the present chloride content in soil to the acceptable level of 700 ppm	Ratio	0 onwards (Ideally 1)	Field Test	Yes	Moderate		
Bedding Stiffness/design stiffness	The ratio of the present bedding stiffness to the designed stiffness of the bedding	Ratio	0 onwards (Ideally 1)	Field Test	Approximate	Moderate		
Soil Corrosivity	Soil corrosivity is influenced by various factors namely soil type, soil disturbance, soil pH, soil resistivity, red-ox potential, chloride content, chloride content, microbial influenced			Field Test	Yes	Moderate		
Soil pH	The range should be 5-8 anything else could give rise to soil corrosivity	pH	0-14	Field Test	Yes	Moderate		
Soil Sulphate	The content of sulphate in the soil. It is measured on a percentage scale	%		Field Test	Yes	Moderate		
Soil sulfide	The content of sulfide in the soil. It is measured on a percentage scale	%		Field Test	Yes	Moderate		
Soil Eration				Field Test	No			
Groundwater Table	The level of groundwater table	Ft		Field Test	Yes	Low		

Appendix P: Condition Assessability Index for Concrete Core Failure

Table 84 illustrates the Calculations of the Condition Assessability Index for Concrete Core Failure of PCCP Water Mains.

Table 84: Calculations of the Condition Assessability Index for Concrete Core Failure of PCCP Water Mains

Influencing Factors	**Explanation for factors**	**Unit**	**Range**	**Associated Technology**	Detectable	Cost	Condition Assessability Index	
	Explanation of the inputs that are required						Performance	Economic Analysis
Curing Time/ Design Curing time	the ratio of the curing time provided for the concrete against the design concrete curing time	Ratio	0 onwards (Ideally 1)	Inspection/ Manual	Yes	Low	**3**	**3**
cement content/ design cement content	The ratio of the observed cement content in the pipe against the design cement content. This is done by taking samples and testing	Ratio	0 onwards (Ideally 1)	Lab Test	Yes	Moderate		
PCCP differences	There are differences in the type of PCCP used in the same network	Level		Inspection/ Manual	Yes	Low		
Concrete Strength/ Design Strength	Ratio of the cast pipe strength to the design strength	Ratio	0 onwards (Ideally 1)	Lab Test	Yes	Moderate		
Aggregate size/design size	Ratio of the aggregate size to the design aggregate size	Ratio	0 onwards (Ideally 1)	Inspection/ Manual	Yes	Low		
Carbonation of concrete	Whether concrete was carbonated or not	yes/ No	Yes- 1, No- 0	Lab Test	Yes	Moderate		

Influencing Factors	**Explanation for factors**	**Unit**	**Range**	**Associated Technology**	Detectable	Cost	Condition Assessability Index	
Difference in pH	Difference in pH	level	0-5	Lab Test	Yes	Moderate		
Water Cement Ratio/ Design Water Cement Ratio	The ratio of the water cement ratio to the design water cement ratio	ratio	0 onwards (Ideally 1)	Lab Test	Yes	Moderate		
Load(dead load + live load)/ Design Load	The ratio of the load acting on the pipe to the load it is designed for	Ratio	0 onwards (Ideally 1)	Field Test	Approximate	High		
Bedding Stiffness/design stiffness	The ratio of the present bedding stiffness to the designed stiffness of the bedding	Ratio	0 onwards (Ideally 1)	Field Test	Approximate	Moderate		
Soil Sulphate	The content of sulphate in the soil. It is measured on a percentage scale	%		Field Test	Yes	Moderate		
Soil porosity				Field Test	Yes	Low		
Soil Moisture Content	The level of moisture content of the soil	Level	Poor Drainage Continuously wet- 2, fairly drainage generally moist-1, good drainage generally dry- 0	Field Test	yes	Low		
Water Corrosivity				Field Test	Yes	Moderate		
Non Uniform Soil	The presence of non uniform Soil	Yes/No		Inspection/ Manual	Yes	Low		

Appendix Q: Condition Assessability Index for Steel Cylinder Failure

Table 85 illustrates the Calculations of the Condition Assessability Index for Steel Cylinder Failure of PCCP Water Mains.

Table 85: Calculations of the Condition Assessability Index for Steel Cylinder Failure of PCCP Water Mains

Influencing Factors	**Explanation for factors**	**Unit**	**Range**	**Associated Technology**	Detectable	Cost	Condition Assessability Index	
	Explanation of the inputs that are required						Performance	Economic Analysis
Manufacturing Inspection	Manufacturing Inspection is inspection for cracks in pipes before the pipes are sent for installation	Level	inspected and no cracks-2, inspected and minor cracks-1, inspected and major cracks-0, not inspected- 1	Inspection/ Manual	Yes	Low	**3**	**3**
cement content/ design cement content	The ratio of the observed cement content in the pipe against the design cements content. This is done by taking samples and testing	Ratio	0 onwards (Ideally 1)	Lab Test	Yes	Moderate		
Encasement	The presence of encasement	Yes/No	Yes-1, No- 0	Inspection/ Manual	Yes	Low		
Design Constructability	The design constructability is the level of difficulty faced by the constructing professionals for laying the pipes	Level	1-5, with 1 being the easy to construct and 5 being difficult to construct	Inspection/ Manual	Yes	Low		

Influencing Factors	**Explanation for factors**	**Unit**	**Range**	**Associated Technology**	Detectable	Cost	Condition Assessability Index	
Installation Inspection/ Orderly Installation	Inspection is required at various phases of the pipe's life. Installation Inspection is the inspection whether the pipes are being laid in the right order as designated.	level	Inspected and installed perfectly- 2, Inspected and not installed perfectly-1, Not inspected- 0	Inspection/ Manual	Yes	Low		
Installation inspection for leaks and cracks	Inspection is required at various phases of the pipe's life. Installation Inspection is the inspection whether the pipes laid are not leaking	level	Inspected and installed perfectly- 2, Inspected and not installed perfectly-1, Not inspected- 1	Inspection/ Manual	Yes	Low		
Post Transportation Inspection	In transportation, there are chances of rough handling which may lead to cracking of the pipes.	Level	inspected and no cracks-2, inspected and minor cracks-1, inspected and major cracks-0, not inspected- 2	Inspection/ Manual	Yes	Low		
Joint coating	The presence of joint coating has to be installed	Level	Presence of joint coating- 2, presence of joint coating but not well coated-1, no joint coating-0	Inspection/ Manual	Yes	Low		
PCCP differences	There are differences in the type of PCCP used in the same network	Level		Inspection/ Manual	Yes	Low		
Concrete Strength/ Design Strength	Ratio of the cast pipe strength to the design strength	Ratio	0 onwards (Ideally 1)	Lab Test	Yes	Moderate		

Influencing Factors	**Explanation for factors**	**Unit**	**Range**	**Associated Technology**	Detectable	Cost	Condition Assessability Index	
Water Cement Ratio/ Design Water Cement Ratio	The ratio of the water cement ratio to the design water cement ratio	ratio	0 onwards (Ideally 1)	Lab Test	Yes	Moderate		
Hydrotest Pressure/ Design Pressure	The Ratio of the Hydrotest pressure to the design pressure of the pipe. Greater Hydrotest pressure cracks the coating	Ratio	0 onwards (Ideally 1)	Field Test	Yes	High		
Surge Pressure/ Design Pressure	The Ratio of the observed surge pressure over the design pressure of the pipe	Ratio	0 onwards (Ideally 1)	Field Test	Yes	High		
Load(dead load + live load)/ Design Load	The ratio of the load acting on the pipe to the load it is designed for	Ratio	0 onwards (Ideally 1)	Field Test	Approximate	High		
Alkali Reactivity Tested/ Design Alkali Reactivity	The Ratio of the tested alkali reactivity of the concrete against the design alkali reactivity	Ratio	0 onwards (Ideally 1)	Field Test	Yes	Moderate		
ppm of chlorides in soil/700ppm	The ratio of the present chloride content in soil to the acceptable level of 700 ppm	Ratio	0 onwards (Ideally 1)	Field Test	Yes	Moderate		
Bedding Stiffness/design stiffness	The ratio of the present bedding stiffness to the designed stiffness of the bedding	Ratio	0 onwards (Ideally 1)	Field Test	Approximate	Moderate		
concrete core stiffness/ spigot ring stiffness				Field Test	yes	Moderate		

Influencing Factors	**Explanation for factors**	**Unit**	**Range**	**Associated Technology**	Detectable	Cost	Condition Assessability Index	
Joint Displacement	The joints can be displaced without undergoing joint misalignment	Type	Joint displaced- 1, Joint not displaced-0	Inspection/ Manual	yes	Low		
Coloration	The Color of the mortar coating is a clear indicator of the condition of the concrete layer	Type	Obvious Rust Strains-5, Moderate Rust Strains-4, Slight Rust Strains-3, No Strains-1	Field Test	Yes	Low		

Appendix R: Condition Assessability Index for Joint Failure

Table 86 illustrates the Calculations of the Condition Assessability Index for Joint Failure of PCCP Water Mains.

Table 86: Calculations of the Condition Assessability Index for Joint Failure of PCCP Water Mains

Stage of the pipe life	**Explanation for factors**	**Unit**	**Range**	**Associated Technology**	**Influencing Factors**	Detectable	Cost	Condition Assessability Index	
The stage of the pipe's life where the required data is to be collected	**Explanation of the inputs that are required**							Performance	Economic Analysis
Installation	Inspection is required at various phases of the pipe's life. Installation Inspection is the inspection whether the pipes are being laid in the right order as designated.	level	Inspected and installed perfectly- 2, Inspected and not installed perfectly-1, Not inspected- 0	Inspection/ Manual	Installation Inspection/ Orderly Installation	Yes	Low	**5**	**3**
Installation	Inspection is required at various phases of the pipe's life. Installation Inspection is the inspection whether the pipes laid are not leaking	level	Inspected and installed perfectly- 2, Inspected and not installed perfectly-1, Not inspected- 1	Inspection/ Manual	Installation inspection for leaks and cracks	Yes	Low		
Installation				Inspection/ Manual	Weld	Yes	Low		

Stage of the pipe life	**Explanation for factors**	**Unit**	**Range**	**Associated Technology**	**Influencing Factors**	Detectable	Cost	Condition Assessability Index	
Installation	The joint fittings should be inspected whether done properly	Level	Joint fitting inspected and fitted properly-2, joint fitting not inspected-1, joint fitting inspected and force fitted- 0	Inspection/ Manual	joint fit up	Yes	Low		
Installation	The presence of joint coating has to be installed	Level	Presence of joint coating- 2, presence of joint coating but not well coated-1, no joint coating-0	Inspection/ Manual	Joint coating	Yes	Low		
Installation	Ratio of the cast pipe strength to the design strength	Ratio	0 onwards (Ideally 1)	Lab Test	Concrete Strength/ Design Strength	Yes	Moderate		
Operations	The Ratio of the tested alkali reactivity of the concrete against the design alkali reactivity	Ratio	0 onwards (Ideally 1)	Field Test	Alkali Reactivity Tested/ Design Alkali Reactivity	Yes	Moderate		
Operations	The ratio of the present chloride content in soil to the acceptable level of 700 ppm	Ratio	0 onwards (Ideally 1)	Field Test	ppm of chlorides in soil/700ppm	Yes	Moderate		
Operations				Field Test	concrete core stiffness/ spigot ring stiffness	Yes	Moderate		

Stage of the pipe life	**Explanation for factors**	**Unit**	**Range**	**Associated Technology**	**Influencing Factors**	Detectable	Cost	Condition Assessability Index	
Operations	Soil corrosivity is influenced by various factors namely soil type, soil disturbance, soil pH, soil resistivity, red-ox potential, chloride content, chloride content, microbial influenced			Field Test	Soil Corrosivity	Yes	Moderate		
Operations	The range should be 5-8 anything else could give rise to soil corrosivity	pH	0-14	Field Test	Soil pH	Yes	Moderate		
Operations	The % of concrete core exposed to moisture without chloride has to be below the limit of 0.15%	%	0.15%	Field Test	Concrete exposed to moisture without Cl-	Yes	Moderate		
Operations	There are different types of cracks	Type	Longitudinal (Spring Line)- 5, Mixed (long+circum)-4, Longitudinal (crown/ invert)-3, Circumferential-2, No Crack- 1	Field Test	Crack Type	Yes	Moderate		
Operations	The width of the crack indicates it seriousness	mm	>= 10 mm - 5, >=5mm- 4, >=1mm- 3, Hairline- 2, No cracks-1	Field Test	Crack Width	Yes	High		

Stage of the pipe life	**Explanation for factors**	**Unit**	**Range**	**Associated Technology**	**Influencing Factors**	Detectable	Cost	Condition Assessability Index	
Operations	Hammer Tapping sound, Hollow Sound, No Sound	Type	Very Firm Tapping Sound-5, Firm Tapping Sound-4, Slightly Hollow Tapping Sound-3, Moderately Hollow Sound-2, Very Hollow Sound-1, No Sound-0	Field Test	Sound Test	Yes	Moderate		
Operations	Shape of the pipe is a clear indicator of the structure of the pipe		Bulge> 3% of the diameter- 5, Bulge between 2% and 3% of the diameter-4, Bulge between 1% and 2% of the diameter- 3, Bulge< 1% of the diameter- 2, No Bulge-1	Inspection/ Manual	Pipe Geometry	Yes	Moderate		
Operations	The alignment of the pipe when compared to the actual placement of the pipes	Type	Angle>22.5 or alignment>11%- 5, 6%< alignment<10%-4, angle<22.5 or alignment<5%- 3, No change-1	Inspection/ Manual	Alignment of the pipe	Yes	Low		

Stage of the pipe life	**Explanation for factors**	**Unit**	**Range**	**Associated Technology**	**Influencing Factors**	Detectable	Cost	Condition Assessability Index	
Operations	The joints can be displaced without undergoing joint misalignment	Type	Joint displaced- 1, Joint not displaced-0	Inspection/ Manual	Joint Displacement	Yes	Low		
Operations	The diaper crack width is measured	Type	>= 10 mm - 5, >=5mm- 4, >=1mm- 3, Hairline- 2, No cracks-1	Field Test	Joint diaper crack size	Yes	Moderate		
Operations	The existence of delamination	Type	Yes- 2, May be-1, No-0	Field Test	Delamination	Yes	Moderate		

Appendix S: Condition Assessability Index for Leaks

Table 87 illustrates the Calculations of the Condition Assessability Index for Leaks of PCCP Water Mains.

Table 87: Calculations of the Condition Assessability Index for Leaks of PCCP Water Mains

Influencing Factors	**Explanation for factors**	**Unit**	**Range**	**Associated Technology**	Detectable	Cost	Condition Assessability Index	
	Explanation of the inputs that are required						Performance	Economic Analysis
Curing Time/ Design Curing time	the ratio of the curing time provided for the concrete against the design concrete curing time	Ratio	0 onwards (Ideally 1)	Inspection/ Manual	Yes	Low	**4**	**3**
cement content/ design cement content	The ratio of the observed cement content in the pipe against the design cements content. This is done by taking samples and testing	Ratio	0 onwards (Ideally 1)	Lab Test	Yes	Moderate		
Installation Inspection/ Orderly Installation	Inspection is required at various phases of the pipe's life. Installation Inspection is the inspection whether the pipes are being laid in the right order as designated.	level	Inspected and installed perfectly- 2, Inspected and not installed perfectly-1, Not inspected- 0	Inspection/ Manual	Yes	Low		

Influencing Factors	**Explanation for factors**	**Unit**	**Range**	**Associated Technology**	Detectable	Cost	Condition Assessability Index	
Installation inspection for leaks and cracks	Inspection is required at various phases of the pipe's life. Installation Inspection is the inspection whether the pipes laid are not leaking	level	Inspected and installed perfectly- 2, Inspected and not installed perfectly-1, Not inspected- 1	Inspection/ Manual	Yes	Low		
Weld				Inspection/ Manual	Yes	Low		
joint fit up	The joint fittings should be inspected whether done properly	Level	Joint fitting inspected and fitted properly-2, joint fitting not inspected-1, joint fitting inspected and force fitted- 0	Inspection/ Manual	Yes	Low		
Joint coating	The presence of joint coating has to be installed	Level	Presence of joint coating- 2, presence of joint coating but not well coated-1, no joint coating-0	Inspection/ Manual	Yes	Low		
PCCP differences	There are differences in the type of PCCP used in the same network	Level		Inspection/ Manual	Yes	Low		
Concrete Strength/ Design Strength	Ratio of the cast pipe strength to the design strength	Ratio	0 onwards (Ideally 1)	Lab Test	Yes	Moderate		
Aggregate size/design size	Ratio of the aggregate size to the design	Ratio	0 onwards	Inspection/ Manual	Yes	Low		

Influencing Factors	**Explanation for factors**	**Unit**	**Range**	**Associated Technology**	Detectable	Cost	Condition Assessability Index	
	aggregate size		(Ideally 1)					
Water Cement Ratio/ Design Water Cement Ratio	The ratio of the water cement ratio to the design water cement ratio	ratio	0 onwards (Ideally 1)	Lab Test	Yes	Moderate		
Load(dead load + live load)/ Design Load	The ratio of the load acting on the pipe to the load it is designed for	Ratio	0 onwards (Ideally 1)	Field Test	Approximate	High		
Bedding Stiffness/design stiffness	The ratio of the present bedding stiffness to the designed stiffness of the bedding	Ratio	0 onwards (Ideally 1)	Field Test	Approximate	High		
Soil Corrosivity	Soil corrosivity is influenced by various factors namely soil type, soil disturbance, soil pH, soil resistivity, red-ox potential, chloride content, chloride content, microbial influenced			Field Test	Yes	Moderate		
Soil pH	The range should be 5-8 anything else could give rise to soil corrosivity	pH	0-14	Field Test	Yes	Moderate		
Soil Chloride	The content of chloride in the soil. It is measured on a percentage scale	%		Field Test	Yes	Moderate		

Influencing Factors	**Explanation for factors**	**Unit**	**Range**	**Associated Technology**	Detectable	Cost	Condition Assessability Index	
Soil Sulphate	The content of sulphate in the soil. It is measured on a percentage scale	%		Field Test	Yes	Moderate		
Soil porosity				Field Test	yes	Low		
Soil Moisture Content	The level of moisture content of the soil	Level	Poor Drainage Continuously wet- 2, fairly drainage generally moist-1, good drainage generally dry- 0	Field Test	Yes	Low		
Water Corrosivity				Field Test	yes	Moderate		
Non Uniform Soil	The presence of non uniform Soil	Yes/No		Inspection/ Manual	Yes	Low		
Concrete exposed to moisture without Cl-	The % of concrete core exposed to moisture without chloride has to be below the limit of 0.15%	%	0.15%	Field Test	Yes	Moderate		
Crack Type	There are different types of cracks	Type	Longitudinal (Spring Line)- 5, Mixed (long+circum)-4, Longitudinal (crown/ invert)-3, Circumferential-2, No Crack- 1	Field Test	Yes	Moderate		

Influencing Factors	**Explanation for factors**	**Unit**	**Range**	**Associated Technology**	Detectable	Cost	Condition Assessability Index	
Crack Width	The width of the crack indicates it seriousness	mm	>= 10 mm - 5, >=5mm- 4, >=1mm- 3, Hairline- 2, No cracks-1	Field Test	Yes	Moderate		
Sound Test	Hammer Tapping sound, Hollow Sound, No Sound	Type	Very Firm Tapping Sound-5, Firm Tapping Sound-4, Slightly Hollow Tapping Sound-3, Moderately Hollow Sound-2, Very Hollow Sound-1, No Sound-0	Field Test	Yes	Moderate		
Pipe Geometry	Shape of the pipe is a clear indicator of the structure of the pipe		Bulge> 3% of the diameter- 5, Bulge between 2% and 3% of the diameter-4, Bulge between 1% and 2% of the diameter- 3, Bulge< 1% of the diameter- 2, No Bulge-1	Inspection/ Manual	Yes	Moderate		

Influencing Factors	**Explanation for factors**	**Unit**	**Range**	**Associated Technology**	Detectable	Cost	Condition Assessability Index	
Alignment of the pipe	The alignment of the pipe when compared to the actual placement of the pipes	Type	Angle>22.5 or alignment>11%- 5, 6%< alignment<10%- 4, angle<22.5 or alignment<5%- 3, No change-1	Inspection/ Manual	Yes	Moderate		
Joint diaper crack size	The diaper crack width is measured	Type	>= 10 mm - 5, >=5mm- 4, >=1mm- 3, Hairline- 2, No cracks-1	Field Test	Yes	Moderate		
Delamination	The existence of delamination	Type	Yes- 2, May be-1, No-0	Field Test	Yes	Moderate		

Appendix T: Condition Assessability Index for Deformed Pipes

Table 88 illustrates the Calculations of the Condition Assessability Index for Deformed Pipes of PCCP Water Mains.

Table 88: Calculations of the Condition Assessability Index for Deformed Pipes of PCCP Water Mains

Influencing Factors	**Explanation for factors**	**Unit**	**Range**	**Associated Technology**	Detectable	Cost	Condition Assessability Index	
	Explanation of the inputs that are required						Performance	Economic Analysis
Installation Inspection/ Orderly Installation	Inspection is required at various phases of the pipe's life. Installation Inspection is the inspection whether the pipes are being laid in the right order as designated.	level	Inspected and installed perfectly- 2, Inspected and not installed perfectly-1, Not inspected- 0	Inspection/ Manual	Yes	Low	**5**	**5**
Installation inspection for leaks and cracks	Inspection is required at various phases of the pipe's life. Installation Inspection is the inspection whether the pipes laid are not leaking	level	Inspected and installed perfectly- 2, Inspected and not installed perfectly-1, Not inspected- 1	Inspection/ Manual	Yes	Low		
Weld				Inspection/ Manual	Yes	Low		

Appendix U: List of the 21 critical data parameters used in Stage 1 Predictability Index for PCCP water main

Stage 1: Evaluation of Severity/ Occurrence and Reliability of Data Parameters

Table 89 illustrates the Calculations of the Condition Assessability Index for PCCP Water Mains with selected 21 data parameters.

Table 89: Stage 1 Calculations of the Condition Assessability Index for PCCP Water Mains with selected 21 data parameters

						This is where the data is to be included by the users	**Here the Users have to justify their data by specifying their level on confidence on the data**		
No:	**Influencing Factors**	**Stage of the pipe life**	**Explanation for factors**	**Unit**	**Range**	**Input**	**Source of Input**	**Severity/ Occurrence**	**Reliability**
		The stage of the pipe's life where the required data is to be collected	**Explanation of the inputs that are required**				Direct Data- 5, Incomplete Data-4, Indirect Data-3, Educated Guess-2, No Data-1	Very High-5, High- 4, Medium-3, Low- 2, Very Low- 1	Very High-5, High- 4, Medium-3, Low- 2, Very Low-1
1	Wire Type	Manufacturing	Wire should not be overheated while drawing lines. Wire manufacturing inspection needs to be	Class	I to IV	4	3	4	3

			done						
2	Weld	Installation	Welding process is a very skillful process and need constant inspection for the final product	Level	inspected and properly welded-2, inspected and minor faults-1, inspected and major faults-0, not inspected- 3	2	4	1	4
3	PCCP differences	Installation	There are differences in the type of PCCP used in the same network	Level			4	3	4
4	Concrete Strength/ Design Strength	Installation	Ratio of the cast pipe strength to the design strength	Ratio	0 onwards (Ideally 1)	0.75	3	3	3
5	Wire Breaks	Operations	The count of wire breaks	Dia- 48" : number	Breaks>= 41-5, 21<=Breaks< 40-4, 6<=breaks<20 -3,<5 breaks-2, no breaks-1	4	3	4	3

				Dia- 96" : number	Breaks>= 81-5, 41<=Breaks< 80-4, 11<=breaks<40-3,<10 breaks-2, no breaks-1	4	3	4	3
6	Surge Pressure/ Design Pressure	Operations	The Ratio of the observed surge pressure over the design pressure of the pipe	Ratio	0 onwards (Ideally 1)	5	4	5	4
7	Load(dead load + live load)/ Design Load	Operations	The ratio of the load acting on the pipe to the load it is designed for	Ratio	0 onwards (Ideally 1)	5	4	5	4
8	Pipe Age/ Design Life of the pipe	Operations	The age of the pipe is not a direct measure	Ratio	0 onwards (Ideally 1)	4	3	5	3
9	Aggressive Water	Operations	The presence of aggressive water flow through the pipeline system	Yes-1/no-0			3	1	3
10	Soil Corrosivity	Operations	Soil corrosivity is influenced by various factors namely soil type, soil disturbance, soil pH, soil resistivity, red-ox				1	3	1

			potential, chloride content, chloride content, microbially influenced						
11	Non Uniform Soil	Operations	The presence of non uniform Soil	Yes/No			4	3	4
12	Corrosion of steel reinforcements	Operations	The observations of corrosion leads to concrete data to support failure of the pipe				3	2	3
13	Crack Type	Operations	There are different types of cracks	Type	Longitudinal (Spring Line)-5, Mixed (long+circum) -4, Longitudinal (crown/ invert)-3, Circumferential-2, No Crack- 1	4	3	4	3
14	Crack Width	Operations	The width of the crack indicates it seriousness	mm	>= 10 mm - 5, >=5mm- 4, >=1mm- 3, Hairline- 2, No cracks-1	4	3	4	3
15	Crack Density	Operations	The spacing between the cracks	mm	Crack Spacing>= 100mm -5, Crack spacing>50-4, Crack	4	3	4	3

					Spacing<=50-3, No cracks-1				
16	Sound Test	Operations	Hammer Tapping sound, Hollow Sound, No Sound	Type	Very Firm Tapping Sound-5, Firm Tapping Sound-4, Slightly Hollow Tapping Sound-3, Moderately Hollow Sound-2, Very Hollow Sound-1, No Sound-0	4	3	4	3
17	Joint Displacement	Operations	The joints can be displaced without undergoing joint misalignment	Type	Joint displaced- 1, Joint not displaced-0		4	3	4
18	Joint diaper crack size	Operations	The diaper crack width is measured	Type	>= 10 mm - 5, >=5mm- 4, >=1mm- 3, Hairline- 2, No cracks-1	4	3	4	3
19	Delamination	Operations	The existence of delamination	Type	Yes- 2, May be-1, No-0	1	3	3	3

20	Coloration	Operations	The Color of the mortar coating is a clear indicator of the condition of the concrete layer	Type	Obvious Rust Strains-5, Moderate Rust Strains-4, Slight Rust Strains-3, No Strains-1	4	3	4	3
21	Leaks	Operations	The volume of leak is measured to verify if it is in the acceptable range or not	Gallon/ Min	0 onwards	5	4	5	4